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RAMJET TECHNOLOGY

Chapter 10

DESIGN OF BAFFLE-TYPE COMBUSTORS

by

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and

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Standard Oil Development Company
ESSO Laboratories

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(Manuscript submitted for publication
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10.1 INTRODUCTION

Combustors in which baffles mounted in the ramjet combustion chamber act as the main source of ignition are treated principally in this chapter. While engines with baffles mounted in one plane perpendicular to the flow axis are distinctly different from can-type burners, baffle burners with baffles slanted in the direction of flow become almost indistinguishable from can burners with longitudinal slots. These latter combustors represent intermediate types which have some of the characteristics of both cans and baffles. Few data are available on these hybrid types, so little discussion of them is included.

Baffle-type combustors have been most generally employed in ramjet applications requiring high thrust per unit frontal area. The relatively low combustor drag is a considerable advantage in this case. However, a higher drag coefficient can be tolerated in low-impulse, high-efficiency burners because the over-all mixture is generally much leaner than stoichiometric, and the diffuser exit Mach number is low. For this application the can combustor is often used because it is able to burn any given part of the air and also mix the hot and cold streams in a relatively short length of tailpipe. However, by use of fuel-confining shrouds and a long tailpipe, low-impulse, high-efficiency performance can also be obtained with baffle-type combustors.

Baffle-type combustors which were studied during the early part of the BUMBLEBEE ramjet program (1945-1946), when only sea-level testing facilities were available, were two-stage combustors such as the 6-inch standard Cobra, the 6-inch shielded-baffle combustors [8], and an early version of the BTV [24]. These had two sets of flame holders, one upstream of the other. The downstream baffles acted both as mixers to help spread the flame coming from the upstream or main flame holders and as starting aids when igniting the engine. These units were excellent for low-altitude missiles, but later simulated high-altitude tests at NACA [24,31] on the 18-inch BTV indicated that a single-stage flame holder (piloted rake) would give better altitude performance than the two-stage igniters previously tested. This led to the use of single-stage combustors in subsequent development of baffle-type combustors. The problem of igniting single-stage combustors in flight (see Section 10.6) was made more difficult because of high-velocity flow and low static pressure at the flame holder. This problem was overcome by incorporating a temporary starting restrictor. By late 1947 only intermediate-altitude conditions could be achieved by existing engines. Emphasis was then placed on the development of ramjet combustors which would burn satisfactorily at high altitude. One such baffle-type combustor to come from this program was the Cobra (L4K). This was accomplished by modification of the standard Cobra and use of a high-burning-velocity fuel. A single-stage flame holder was employed because previous results indicated this to be better for high altitude operations. Cross gutters replaced the Y-gutters on the end of the tracer holder. As shown in flame spreading studies (Chapter 8), the extra gutter should help from an efficiency standpoint (closer spacing between baffles), however, the most significant gain in efficiency came from changing to propylene oxide as fuel. The L4K had an oxygen-fed pilot system which gave wider stability limits for the same operating conditions.

Other units developed around a single-stage set of flame-spreading elements, but using kerosene or gasoline fuel, were the XPM, 20- and 28-inch Marquardt engines, 14-1/2-inch UAC (United Aircraft Corporation) engines, and the 16- and 20-inch NACA engines. The later engine models use pilots which have been found necessary for adequate high-altitude stability. Small piloted annular wall-baffle burners were also investigated by the United Aircraft Corporation for use in a cluster arrangement in multi-unit ramjets.

As shown in Chapter 3, the size of the combustion chamber, along with the entrance and exit flow conditions, is usually set from consideration of the over-all missile requirements. It is then up to engine designers to construct an engine that will operate within these given limits. Since the two chief criteria of combustor design are stability and combustion efficiency, it is essential that the effect of flame holder geometry, pressure, temperature, velocity, air-fuel ratio, air-fuel distribution, and fuel type, be known for baffle-type ramjet applications. Since measures taken to improve stability usually tend to increase internal drag losses, methods of estimating these losses are necessary. Ignition, instability, and burnout are other problems of importance. In this chapter these subjects are discussed in approximately the above order. The design and performance of specific combustors which serve to illustrate advantages or disadvantages or certain design features are given in the appendix. Due to the lack of available information, the survey does not include all existing baffle-type engines and their variations.

10.2 COMBUSTOR STABILITY

Ramjet engines for a given application must operate over a specified air-fuel ratio range at specified operating conditions. The variables affecting stability are treated in the following groups.

1. Baffle size and inlet air stage,
2. Baffle arrangement and fuel-air distribution, and
3. Fuel type and fuel vaporization.

The range of air-fuel ratios over which smooth combustion takes place defines the stability limits for any given operating condition. In most cases these limits are true blow-outs, the flame in the recirculation zone of the baffle being completely extinguished. Although some degree of pressure oscillation is present in all combustors, under certain conditions large pressure fluctuations may occur causing structural damage or burnout. The range of burning which produces the less harmful pressure fluctuations would be considered the operable range for actual missile application. A brief discussion of the causes of rough burning, and methods of eliminating it, may be found in Section 10.7.

Baffle Size and Inlet Air State

The principles of flame stabilization by simple baffles in a homogeneous air-fuel mixture have been covered in Chapter 8. It was shown, for practical-size flame-holding elements, that the burning range for various pressures, sizes, shapes, and velocities could be correlated by use of the group U/NP; where U is the mixture velocity past the baffle, N is twice the mean hydraulic radius of the baffle, and P is the static pressure at the baffle.

Figure 10.2-1 shows the effect of pressure and gutter width on the smooth-burning range of a typical baffle-type combustor. The Marquardt engine [1] had a 28-inch-diameter combustion chamber in which was mounted various numbers of annular V-gutters. The runs were made with a fixed fuel-injection system consisting of two internal fuel-manifold rings with spring-loaded, fuel-spray nozzles located approximately one combustor-chamber diameter upstream of the flame holders. A fairly uniform fuel-air mixture profile resulted from this arrangement. The smooth-burning range was decreased as the gutter width was decreased, or for a given gutter-width configuration, the burning range was decreased as the combustion chamber exit pressure was reduced. The inlet velocity was approximately constant for all the above conditions in the region of stoichiometric air-fuel mixtures. This shows that pressure and baffle size have directionally the same effects on the stability limits of full-scale combustors as on the simplified baffles in Chapter 8. The effect of baffle size is further shown in Fig. 10.2-2 where the same data are plotted as U/N versus equivalence ratio. This curve is very similar to those found for simple baffles except that it is shifted to the lean side due to nonhomogeneous air-fuel mixtures.

In Fig. 10.2-3 is shown the effect of velocity and pressure on the smooth-burning air-fuel range of a variation of the above combustor [2,3]. The same engine was tested with different sizes of exit nozzles as noted on the curve. Near the pinch-off points at low-inlet static pressures, the entrance velocity was approximately 195 ft/sec for the 55 per cent exit-nozzle configuration and approximately 285 ft/sec for the 65 per cent exit-nozzle configuration. It is noted that at lower inlet-velocity conditions, the engine could be operated at lower pressures before reaching the stability pinch-off. The range of

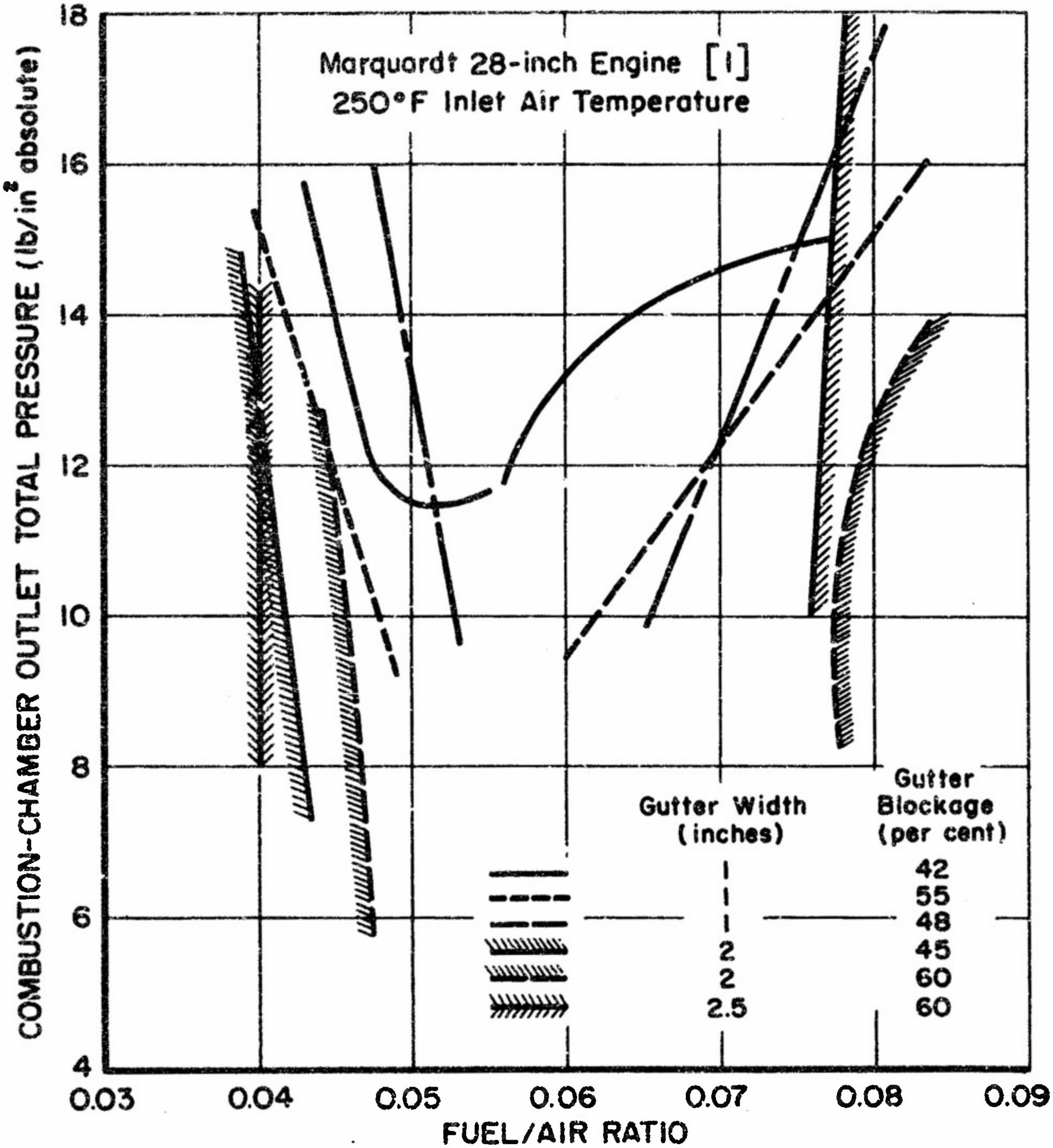

Fig. 10.2-1 EFFECT OF PRESSURE AND BAFFLE SIZE ON STABILITY LIMITS

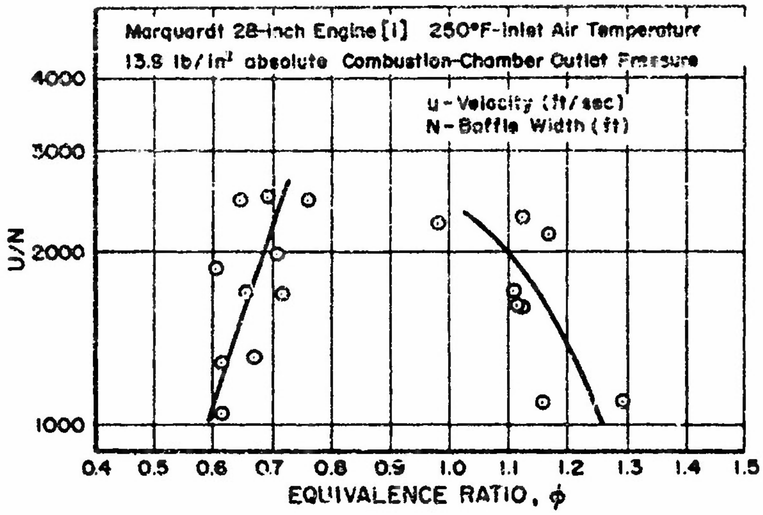

Fig. 10.2-2 CORRELATION OF STABILITY LIMITS

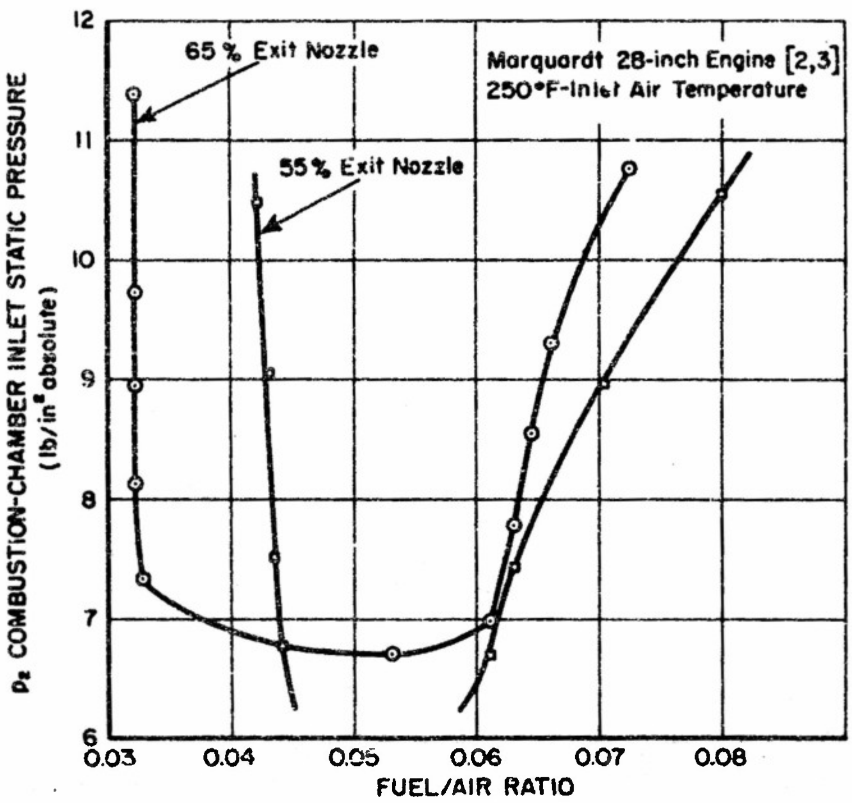

Fig. 10.2-3 EFFECT OF VELOCITY AND PRESSURE ON SMOOTH-BURNING RANGE

smooth burning in the higher pressure region is different in the two cases, probably due to differences in air-fuel distribution. Apparently the inlet velocity affects the fuel-spray pattern in this engine. Again the stability limits are shifted to the lean side compared to the pinching-off at an air-fuel ratio of 0.066 (stoichiometric) for simplified baffles in a homogeneous air-fuel mixture. The qualitative effect of velocity is as predicted from simplified baffle experience.

The effect of inlet-air temperature on the smooth-burning range of a typical ramjet combustor is shown in Fig. 10.2-4 where wider limits are obtained at the higher temperatures. This observation is the same as reported in Chapter 8 for simplified baffles, where it was shown that for a practical-size baffle operating at constant pressure, the smooth-burning range could be correlated by combining the temperature and velocity into the group $U/T^{1.2}$. As already noted in Fig. 10.2-4, at a fuel-air ratio of 0.055, the 150- and 350-degree curves give about the same limiting pressure. The combustion-chamber-inlet velocities were lower in the 150-degree case so that $U/T^{1.2}$ values at the two temperatures were approximately equal. Also the lower-temperature curve has the added effect of having more unvaporized fuel at the flame holder causing the general shape of the curve to change.

Since the factors affecting the stability of the flame show similar relationships in both full-scale engines and simple baffles, it is of interest to observe how the different systems behave when correlated by use of the group U/NP. This has been done and the criterion of stability has been plotted as a function of equivalence ratio in Fig. 10.2-5, for both simple baffles and ramjet engines. The maximum value of U/NP for complete combustors was assumed to occur at $\phi = 1.0$, although the actual measured over-all equivalence ratio was different because of the non-homogeneous fuel system used in the actual combustor.

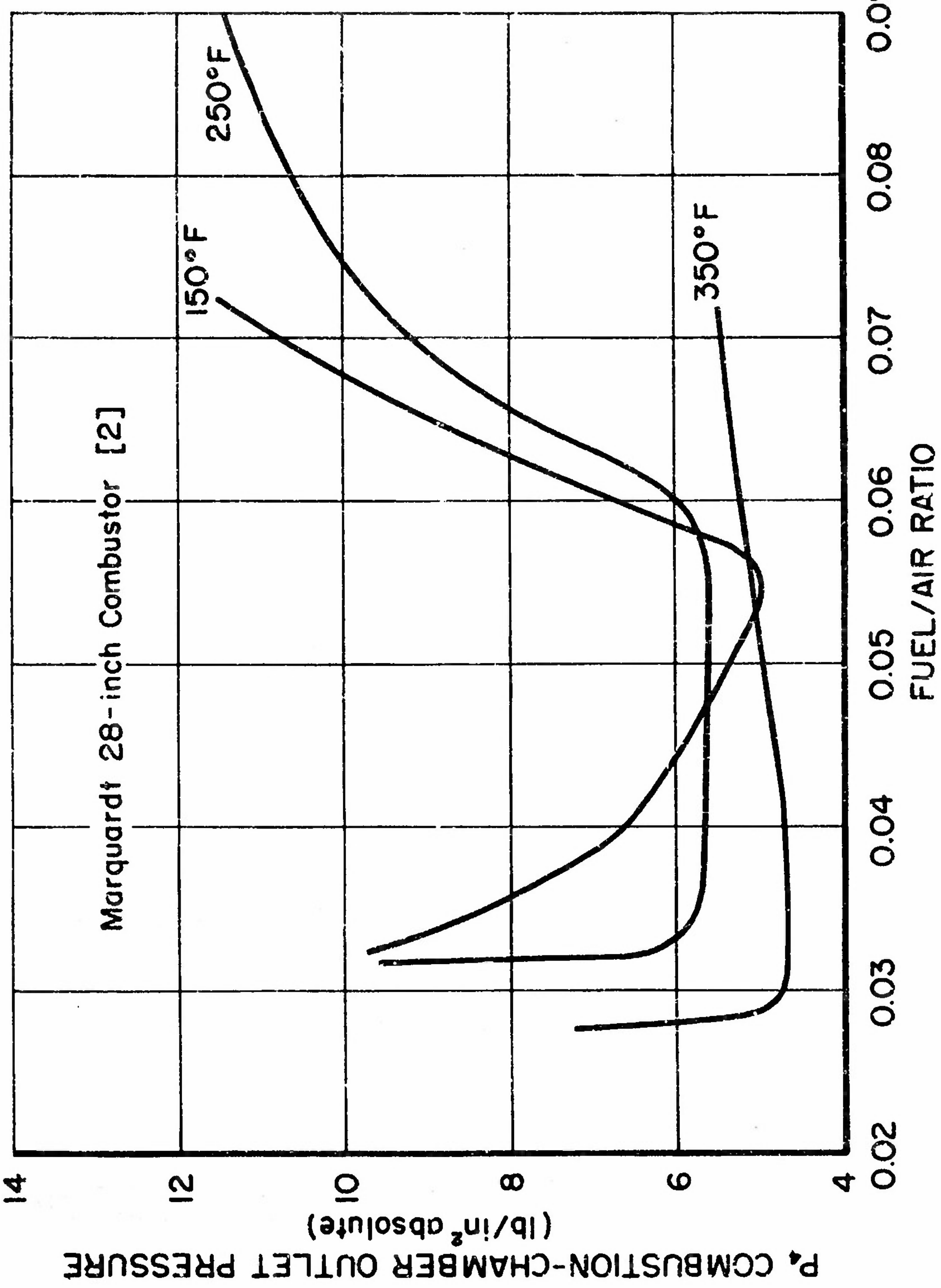

Fig. 10.2-4 EFFECT OF INLET AIR TEMPERATURE ON SMOOTH-BURNING RANGE

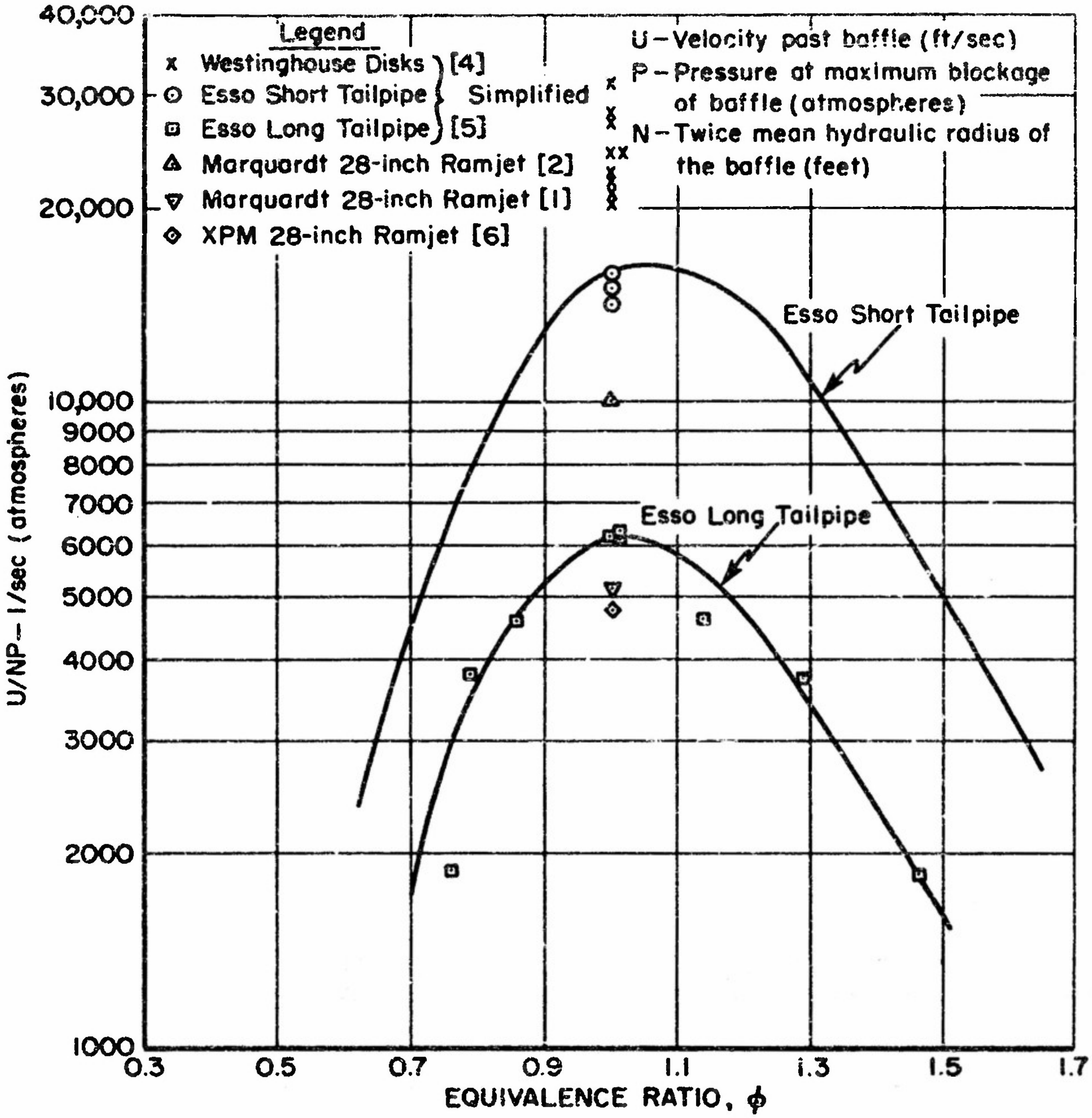

Fig. 10.2-5 STABILITY CHARACTERISTICS OF SIMPLIFIED FLAME HOLDERS AND COMPLETE BAFFLE-TYPE COMBUSTORS

The curve in Fig. 10.2-5 is the result of stability tests on simplified flame holders made at the Esso Laboratories [5] with a short tailpipe (see also Chapter 8). Data for the long tailpipe are shown as open squares, and it may be seen that the addition of tailpipe length has considerably reduced the stability. Measured pressure fluctuations in the long-tailpipe system were higher than in the short- or open-tailpipe system. This difference in pressure fluctuations is probably related to the difference in blowout limits. The crosses represent the blowout limits at $\phi = 1.0$ for the Westinghouse data [4] taken at various pressures, this equipment being somewhat more stable than Esso short-tailpipe equipment. It is believed that the basic difference between these two was the higher level of turbulence in the Esso apparatus.

The inverted triangles of Fig. 10.2-5 represent results obtained by the NACA [1] on a Marquardt 28-inch ramjet which consisted of four annular V-gutters, 1.0 inch wide. The maximum value of U/NP for this unit is less than that of the idealized long-tailpipe unit. On the other hand, the open triangles represent data on a later Marquardt combustor [2] in which a large cylindrical baffle mounted in the center of the duct acted as a pilot (see Section 10.4 for pilot-design details) for two 2-inch-wide annular gutters. In this case, the characteristic dimension, N, was taken as 2.22 inches (mean hydraulic radius of all gutters). The addition of this pilot results in a marked increase in stability. XPM [6], a similarly constructed ramjet, shows lower stability than the Marquardt unit. This lower stability can probably be attributed to rougher flow through the subsonic diffuser and to a lower pressure fuel-injection system.

No single stability curve was obtained for the different systems, but it can be shown that the general shapes of all these curves are the same. This suggests the use of a "design

factor" to give a single base stability curve. The values of these "design factors" for different systems and the accuracy within which a single stability curve might fall may only be determined by a great deal of further study on the effect of turbulence, pressure fluctuation, and multi-element interference. At present the design factor must be chosen by analogy of a proposed burner to those already tested.

Baffle Arrangement and Fuel-Air Distribution

In an actual ramjet combustion chamber, a nonuniform distribution of air and fuel generally occurs. For a given engine configuration, the range of smooth burning depends partly on this distribution. Data are available [7] illustrating the effect of fuel distribution on performance of a combustor (Fig. 10.2-6) in which the flame-holding element is a 3-1/2-inch-diameter shielded baffle into which an air-fuel mixture is bled through a 0.2-inch annular slot. The downstream-gutter flame holders serve only to spread the flame and do not, except possibly for induced pressure oscillations, affect the performance of the baffle.

Fuel was injected through the four needles, and the distribution was altered by changing the radial positions of these needles. The indicated fuel shield was used in cases in which a very high fuel-concentration gradient was desired between the baffle and the duct wall. Ratios of local A/F ratios to overall A/F ratios were varied from 0.4 to about 2.0. Fuel distributions were measured 3/8-inch downstream of the baffle and showed no deviation from distributions measured inside the baffle.

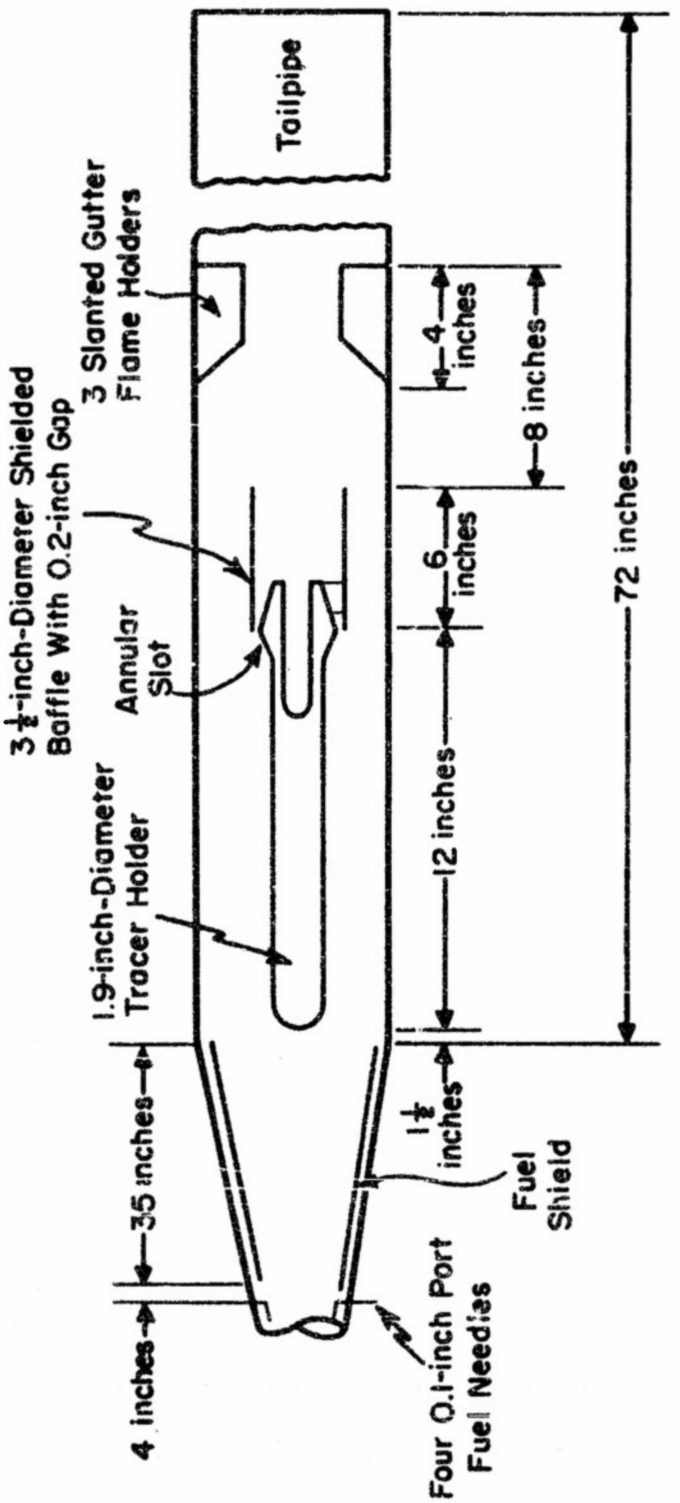

Fig. 10.2-6 SKETCH OF SIMPLIFIED BAFFLE, SLANTED-GUTTER COMBUSTOR

The table below presents the results obtained, showing that the smooth-burning range of the baffle, depends not on the over-all A/F ratio, but specifically on the A/F ratio inside the flame stabilizing element, i.e., the baffle.

Effect of Fuel Distribution on the Shielded Baffle Combustor

Fuel Distribution	Over-all Smooth-Burning Range - A/F	Local (at baffle) Smooth-Burning Range - A/F
A	16.9 - 28.4	11.0 - 17.4
B	18.5 - 29.0	10.3 - 16.2
C	15.1 - 25.4	10.6 - 19.2
D	16.6 - 26.2	10.5 - 18.4
E	24.7 - 35.7	10.7 - 17.6
F	-- - 22.2	-- - 18.7
	Average	10.6 - 17.9

It may be noted that the average limits of 10.6 - 17.9 are narrower than the 9-23 that would be predicted by the U/NP correlation for results from cylindrical baffles operating with homogeneous mixtures and short tailpipes.

The operational requirements of a ramjet may dictate that the combustor must operate over a wider smooth-burning range than is possible for the centrally-located type combustor. One method for solving this problem is to use a continuous-flame-holding element that cuts sections of various air-fuel mixtures. Then within a wide range of air-fuel ratios some part of the flame holder would be in a region of a combustible local air-fuel ratio. A typical flame holder [7] of this type is the Y-gutter (Fig. 10.2-7), a baffle in which the three legs of the Y are 120 degrees apart and radiate from the duct center to the wall. Tests have been made with a 3/4-inch Y-gutter mounted in

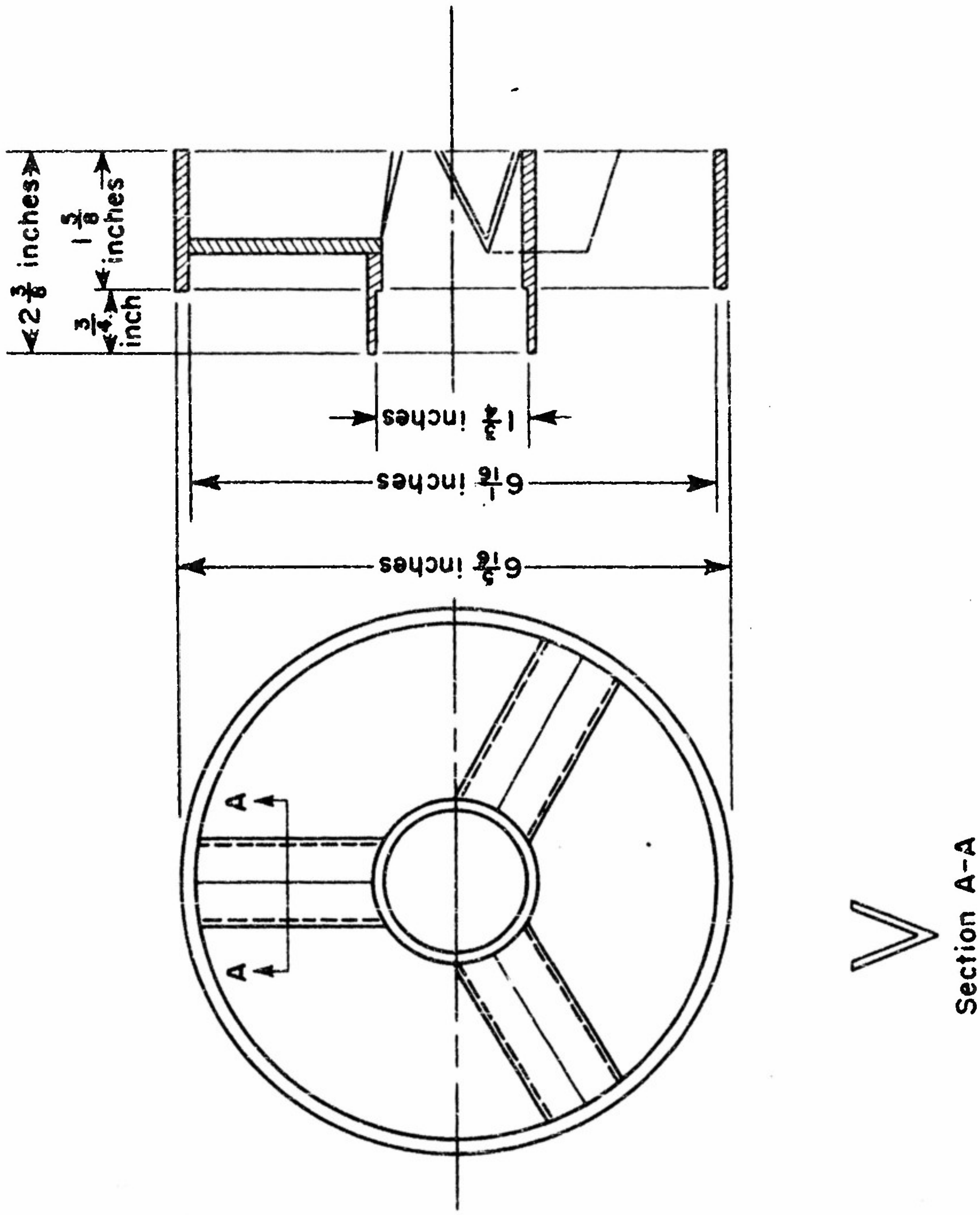

Fig. 10.2-7 Y-GUTTER FLAME HOLDER

a 6-inch duct in which the fuel distribution was again varied by radial positioning of the fuel-injection needles. Smooth-burning limits were recorded, and fuel-distribution surveys taken immediately downstream of the gutter along a line that bisected the gutter (along one element for half the duct diameter, and between the other two elements for the other half diameter). In Fig. 10.2-8 the effect of changing the needle-injection position on the relative air-fuel-ratio distribution is shown for the two-stage-injection system operating at an average air-fuel ratio of 33. The right side of the curve illustrates conditions immediately downstream of the gutter. In cases Q and R the concentration gradients are noticeably less steep than for the part of the traverse between gutters. This indicates circulation of the rich mixture from the center of the combustor outward along the gutter to the wall. The fact that red hot streaks on the tailpipe occur even under conditions where the average concentration near the tailpipe wall is not sufficiently high to heat it to that temperature indicates that a considerable amount of fuel is transferred from the center to the wall in this manner, giving a higher concentration directly in the wake of the radial gutter. As the fuel-injection needles are moved toward the center, the concentration gradient between the radial gutters increases and the maximum fuel concentration at the tracer wall increases. For the two curves Q and R in Fig. 10.2-8, the lean limits are nearly the same, 35 and 37, and the maximum fuel concentrations are observed to be nearly the same. The other curve, for a burner with a lean limit of 18.5, has a considerably leaner mixture at the point of maximum concentration. Examination of the data from several burners of this type for which fuel-concentration traverses have been made indicates that the

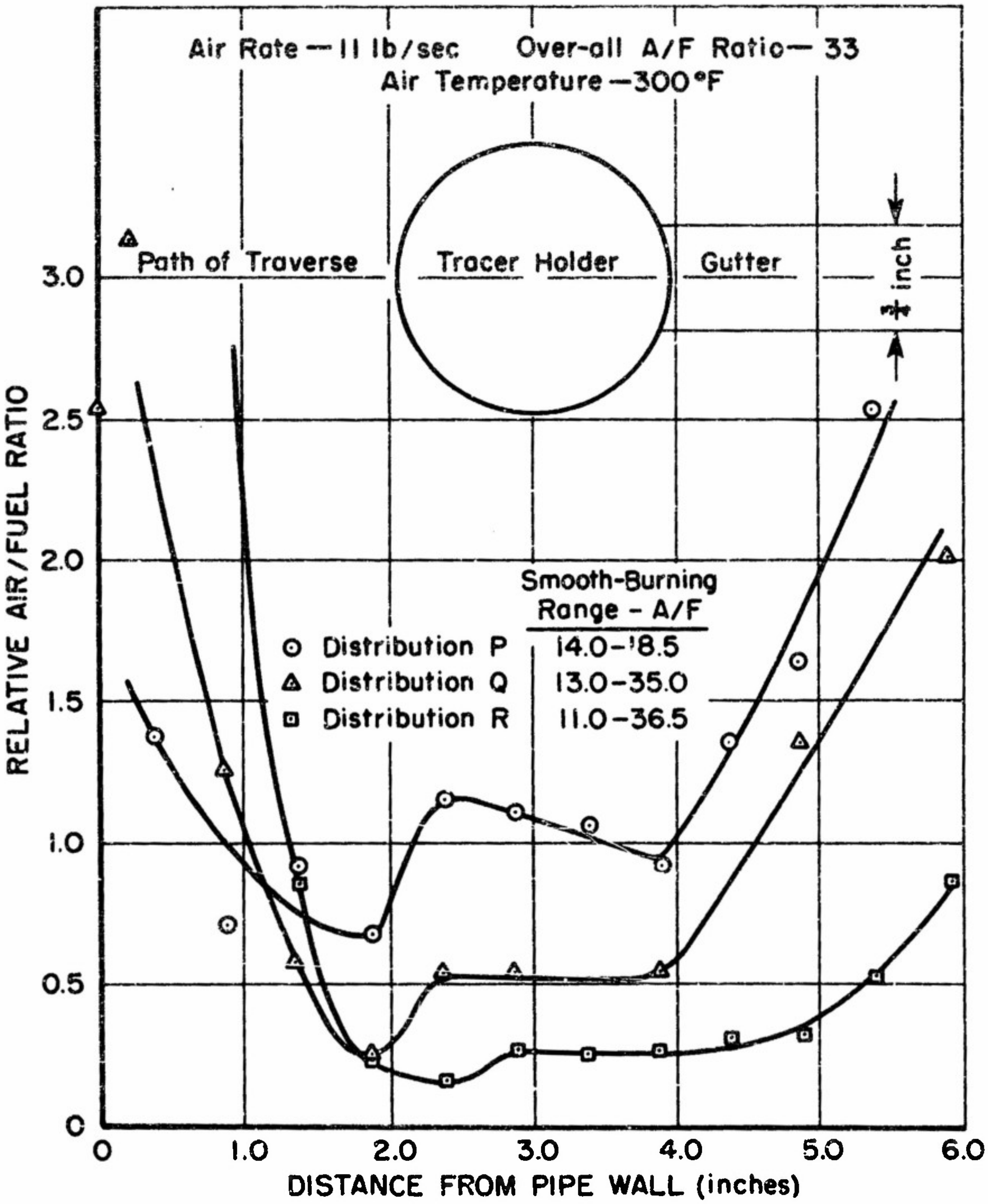

Fig. 10.2-8 RELATIVE AIR-FUEL DISTRIBUTION
0.38 INCH BEHIND Y-GUTTER

best correlation of lean limit operation is obtained with the minimum air-fuel ratio measured in the traverse. The table below shows the minimum air-fuel ratio existing at the average air-fuel ratio at which blowout occurs. As might be expected this air-fuel ratio is not always the same; however, the variation is not wide and there seems to be a definite correlation.

Minimum Air-Fuel Ratio at Lean Limit Blowout for Y-Gutter Combustor

Distribution	Range of Smooth Burning	Minimum Air-Fuel Ratio
P	14 - 18.5	11.5
Q	13 - 35.0	9.7
R	11 - 36.5	7.0
T	18 - 35.0	11.1
U	11 - 33.4	9.1
S	22 - 35.0	10.5

These numbers will apply only to this particular type flame holder; however, the observation that quite rich local mixtures must exist to allow piloting of a very large volume of air-fuel mixture from a relatively small source is probably generally valid under these operating conditions.

It is shown [30] that certain pressure fluctuations (rough burning) are associated with rich air-fuel mixtures in the boundary layer along the combustion-chamber wall. In the case of the Y-gutter combustor above, the unit became rough just before rich blowout. On this basis one might expect a shifting of the rich limit to richer values of over-all air-fuel ratios as the amount of fuel along the wall was decreased.

For this particular flame holder, a change in concentration gradient from about 3 to 13 (units of A/F ratio per inch) caused a linear change in the over-all A/F ratio at the rich limit from about 21 to 11 respectively. Again, these specific numbers apply only to this particular configuration, but there is some additional evidence from work on larger-scale combustors that the amount of fuel along the wall is an important factor in rich-limit performance.

Tests have been made on a 20-inch Marquardt combustor [11] in which the flame-holding elements consisted of several annular gutters located in the same cross-section. The fuel distribution consisted of quite lean mixtures near the innerbody and outer duct walls with a fairly rich A/F ratio in the middle of the annular space between the walls; the maximum local A/F ratio was of the order of ten times the minimum (richest) A/F ratio. It is of interest to note that at the lean blowout, the annular gutters would go out one at a time with the gutter in the region of the richest mixture the last to be extinguished. With this combustor, an extended over-all lean limit A/F ratio (45.5) was obtained. This results from the fact that with a number of flame holders cutting different parts of a nonhomogeneous fuel-distribution curve, the extinguishing of one does not affect flow conditions severely enough to extinguish the others. Therefore, with severe fuel-concentration gradients, the location of any one flame holder in a combustible mixture permits the combustor to operate through an extended range. This performance is in distinction to that of the XPM [6] which has a very large central pilot and in which extended lean performance is more difficult to obtain. Here, when the central pilot blows out (and its stability depends on a specific local mixture) there is a severe effect on flow conditions, and total blowout is likely. Effects similar to the 20-inch Marquardt engine's

behavior are noted in can-type combustors which operate to very lean A/F ratios, if there are high concentration gradients in the upstream zone. A properly designed can may be thought of as consisting of a great many flame-holding elements, and the blowout of any few individual segments seems to have little effect on the others, giving smooth burning over a wide stability range with nonuniform fuel distribution.

Fuel Type and Vaporization

In Chapter 5 the various fuels that can be used in ramjet engines are discussed. Although a few special fuels (for example, propylene oxide) give wider stability limits than hydrocarbon fuels in the kerosene-gasoline range, a properly designed engine and fuel injector should be able to satisfy all the missile's operating requirements with saturated hydrocarbons. Other factors besides the burning characteristics (see Chapter 5) must be considered in choosing a fuel. The stability of a specific engine will remain about the same when using different hydrocarbon fuels providing all the fuel is vaporized when it reaches the flame holder and the air-fuel distribution remains the same.

The smooth-burning range of a combustor may be greatly affected by the degree of evaporation of the fuel arriving at the flame holders. The amount of fuel vaporized depends on many factors -- distance from the point of injection to the flame holders, fuel volatility, liquid drop size, drop distribution, inlet-air temperature, inlet-air velocity, drop-collection efficiency of the flame holder, obstructions between injector and flame holder, and temperature of the flame holder surface. Although Chapter 7 gives methods of predicting the air-fuel distribution and the amount of fuel vaporized under

equilibrium conditions of the inlet-air stream, there is no way at the present time to estimate accurately the fuel-phase distribution at the plane of the flame holder when unvaporized fuel is present at that station.

Some discussion of the effect of liquid and partially vaporized fuel on the stability of simple baffles can be found in Chapter 8. Tests at the Esso Laboratories [8] on 6-inch baffle engines generally indicate that as less fuel is vaporized, the stability limits shift to the rich side. Although the overall air-fuel ratio is rich, the actual air to vaporized fuel ratio behind the gutter is much leaner. In a mixture containing liquid fuel, and under specially controlled conditions, very wide stability limits can sometimes be obtained. The rich limit becomes richer mainly for reasons stated above, but the lean limit is extended (made leaner) by allowing fuel to collect and vaporize from the surface of the flame holder. In the case where both the rich and lean limits shift to the rich side, most of the air-vaporized fuel mixture behind the baffle comes from fuel vaporized in the air stream while the case with the extended limits, the air-vaporized fuel mixture behind the baffle is further enriched by the fuel which collects and vaporizes from the surface of the baffle. One can see that designing a complete engine to operate with extended limits when liquid fuel is present at the flame holders is very difficult.

It was shown in the section on baffle arrangement and fuel-air distribution that some of the 6-inch Esso combustors operating with completely vaporized fuel became rough as the rich limit was approached. If the air-fuel distribution was changed to give lean mixtures along the combustion-chamber wall, this rough burning disappeared. However, smooth burning near the rich limit could also be obtained with a fairly uniform air-fuel distribution if the fuel were partially vaporized when arriving at the flame holders. Apparently having liquid fuel on and near the wall prevents flashback in the boundary layer.

Design Recommendations for Stability

From the foregoing paragraphs it can be concluded that to obtain the maximum stability from a ramjet engine, the combustor must be matched with a good diffuser design. The flow entering the combustion chamber should be smooth and have a low level of turbulence. This not only holds from a stability standpoint, but as will be shown later it is important for good efficiency and elimination of certain burnout problems. Some design recommendations may be made from the stability characteristics of simple flame holders and complete baffle-type combustors shown in Fig. 10.2-5. First, if a clean aerodynamic (turbulence, boundary layer, etc.) diffuser exists, the combustor made up of baffle elements alone will probably have a pinch-off point in the range found for the Esso long-tailpipe unit and the 28-inch, unpiloted, Marquardt engine (inverted triangle). Second, with the same clean diffuser design, the stability pinch-off may be increased by use of a pilot as demonstrated by the 28-inch piloted Marquardt engine (triangle). Thus by the use of apilot with a specified stability range, the designer could at least double the velocity past the gutters or operate the unit at a pressure level half again lower than an unpiloted combustor. Third, if a poor or unstable diffuser exists, the stability pinch-off will be reduced as shown by the piloted XPM engine (diamonds).

A given combustor-diffuser combination will then operate, with a uniform air-fuel distribution, between the limits of a certain stability curve. To insure a margin of safety, the value of U/NP used for design purposes should be greater than the U/NP anticipated to give the desired smooth-burning range at maximum altitude. The size, blockage, spacing, etc. of the baffles for a specific combustor depends not only on the stability but also on the desired combustion efficiency and drag.

Actually the final design will be a compromise of all these factors. The designer must now produce an air-fuel distribution such that the homogeneous stability curve is shifted to the smooth-burning range dictated by the missile requirement. This is done by insuring, over the smooth-burning range required, that some of the elements always are in a region of flammable mixture. The fuel distribution thus chosen can be obtained by designing the fuel-injection system according to methods outlined in Chapter 7. Again a compromise design might be sought because the combustion efficiency is dependent on the air-fuel distribution. Other factors to be considered are tailpipe cooling or eliminating rough burning by lean mixtures at the wall. If the stability range cannot be met by injecting fuel through all the needles then some needles may be cut out during operation to give a change in air-fuel distribution. This principle has been applied on a Marquardt 28-inch combustor [2] where very wide stability limits were obtained. For rich air-fuel mixture operation, two fuel manifold rings with spray nozzles attached (located 28 inches upstream of the flame holder) are utilized to give a fairly uniform air-fuel distribution and for lean air-fuel operation, one fuel ring (fuel to other ring turned off) is utilized to give high local concentration. Another method of concentrating the fuel in a particular portion of the combustor is the use of fuel shields. With various shields and fuel injectors, very wide stability limits can be obtained. Tests were made by NACA [19, 39,40] on a number of shield-injector configurations in 16- and 20-inch engines. As will be shown in the section on fuel-air ratio and fuel-air distribution, by using the shields to control mixing as well as fuel concentration, very good efficiencies are obtained at lean fuel-air ratios. One disadvantage of shields is the added weight and drag; however, the gains in both efficiency and stability might be more important than this disadvantage.

10.3 EFFICIENCY

Design for adequate spreading of the flame from the baffle elements through the unburned mixture flowing past, in order to attain a high efficiency at the combustion-chamber exit, is considered in this section. In general, the relations among combustors, combustor length, and efficiency are discussed as a function of the various flow and design variables. As shown in Chapter 8, flame spreading is a complex problem because, in part, it is a function of the degree of mixing behind baffles and the turbulence of the entering air stream. Besides all the variables affecting flame spreading found in simplified baffle studies, the combustor for ramjet application has additional variables that should be considered. For example, one must consider the degree of vaporization of the fuel as it passes by the flame holders along with the fuel concentration gradient that usually exists across this section of the full-scale combustor. In some cases the fuel concentration fluctuates with time which affects the over-all combustion efficiency.

It is important, for obvious reasons, that the exit thrust from the engine be as high as possible for a given amount of input fuel. It has been found in certain combustors with nonuniform fuel distribution that, although the fuel is completely burned (100 per cent chemical efficiency), the efficiency based on exit thrust is lower than expected. This happens when there is poor mixing of the gases downstream from the baffle elements with resultant steep temperature profiles at the combustion-chamber exit. Most of the combustor configurations used as examples in this section have a fairly uniform fuel distribution so that the reported efficiencies are chemical in nature (uniform temperature profile) and comparable to those from simplified baffle experiments.

The variables affecting combustion efficiency in baffle-type ramjet engines are discussed in the following order.

1. Inlet-Air State
    a. Velocity
    b. Pressure
    c. Temperature
2. Flame Holder Geometry
3. Pilots
4. Air-Fuel Ratio and Air-Fuel Distribution
5. Fuel Vaporization and Fuel Type
6. Turbulence
7. Comparison of Predicted and Actual Tailpipe Lengths
8. Design Recommendations for Efficiency

Inlet-Air State

Examples from full-scale engines and simple baffles should illustrate the effect of inlet velocity, temperature, and pressure on combustion efficiency. Combustion-chamber inlet Mach numbers of existing ramjet engines range from about 0.11 to 0.24 when the units are operating near their peak efficiencies. At lean air-fuel ratios and usual accompanying lower efficiencies, the inlet Mach number increases. A lower temperature limit of 150 degrees Fahrenheit may be found in some designs for realistic flight Mach numbers at high altitude. Inlet pressure varies with flight Mach number, diffuser efficiency, and altitude. Although some engines operate at 1/3-atmosphere combustion-chamber pressure, the usual minimum pressure is about 1/2-atmosphere.

Figure 10.3-1 illustrates the effect of inlet Mach number (velocity) on combustion efficiency over a range of fuel-air ratios. The combustor [2] was 28 inches in diameter and consisted

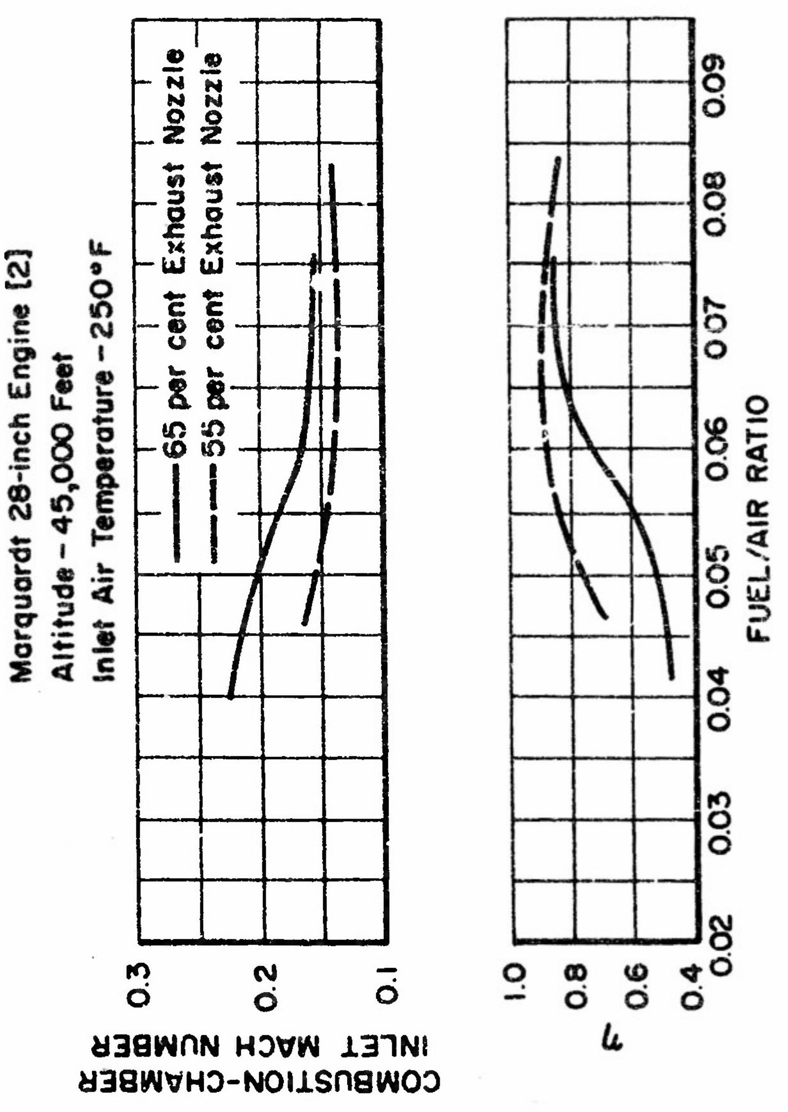

Fig. 10.3-1 EFFECTS OF EXHAUST NOZZLE SIZE ON COMBUSTION VARIABLES

of two 2-inch wide annular V-gutters with a 7.8-inch diameter central pilot. The unit was tested with two sizes of exit nozzle. The results are typical of baffle-type combustors in that higher efficiencies are obtained at the lower inlet-velocity condition. At an air-fuel ratio of 0.065, the above combustor has an inlet Mach number of 0.165 (216 ft/sec) for the 55 per cent exhaust nozzle with a resultant efficiency of 82 per cent. The flame-spreading correlation of Chapter 8, for the same air-fuel ratio, would predict that the 65 per cent nozzle combustor at an inlet Mach number of 0.135 (177 ft/sec) has a corresponding efficiency of 90 per cent. This is in very good agreement with the results from the full-scale combustor above.

The effect of inlet temperature (Fig. 10.3-2) is illustrated by data taken on the 65 per cent exit nozzle combustor [9] described above in which normal heptane was used as fuel. The results were similar to those shown in Chapter 8 in which higher efficiencies resulted from higher inlet-air temperatures. The flame-spreading correlation for simple baffles would predict for the high pressure curve of Fig. 10.3-2, that going from a temperature of 220 degrees Fahrenheit at an efficiency of 74 per cent, an efficiency of 85 per cent should be obtained if the temperature is increased to 340 degrees Fahrenheit. This is very close to the actual value of 84 per cent obtained in the full-scale combustor. The temperature effect is further demonstrated by results from XPM tests [10] which are plotted in Fig. 10.3-3. Again higher efficiencies occur at higher temperatures for the same inlet pressure and velocity.

The pressure effect is also shown in Fig. 10.3-3 with results similar to those found with simple baffles; that is, efficiency drops off at lower combustion-chamber inlet pressures. The correlation on flame spreading behind simple baffles (Chapter 8) showed that the pressure dependency of a system is a

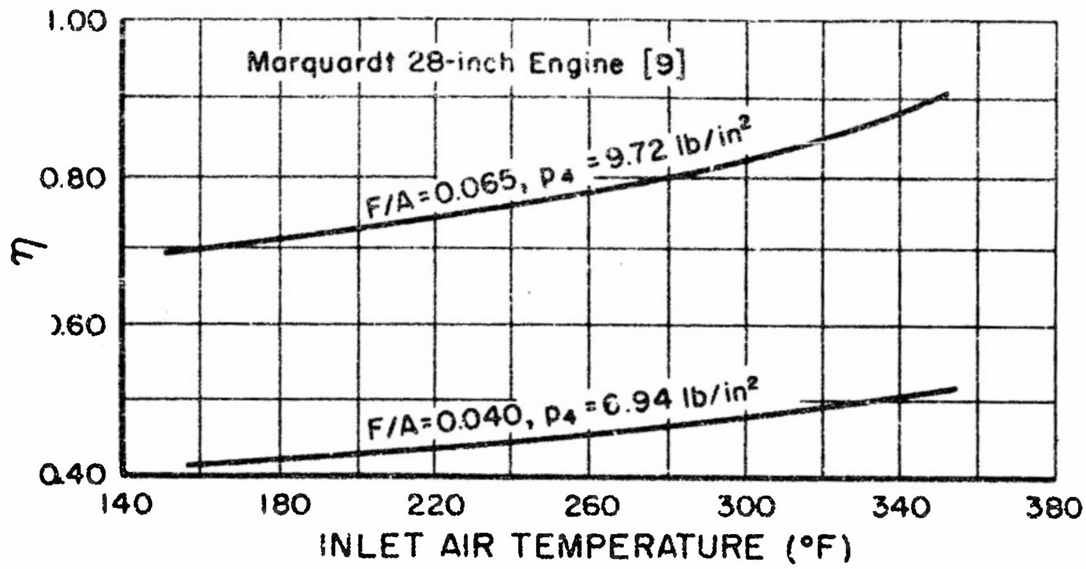

Fig. 10.3-2 EFFECT OF INLET AIR TEMPERATURE ON COMBUSTION EFFICIENCY

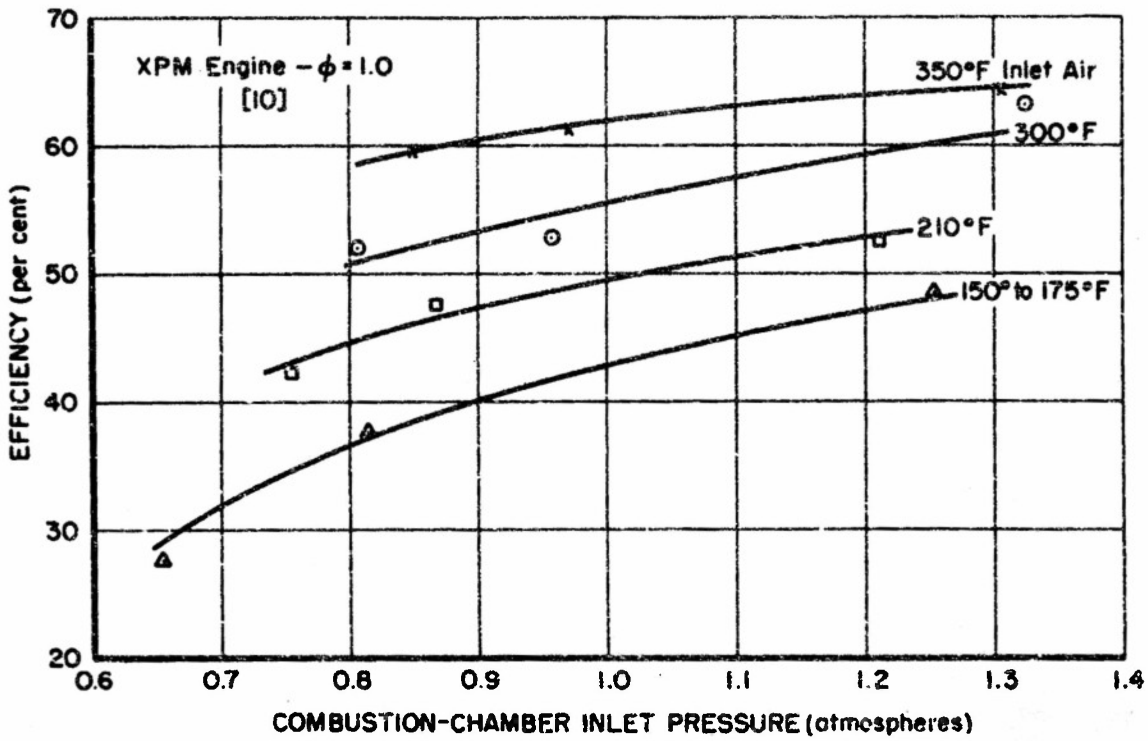

Fig. 10.3-3 EFFECT OF TEMPERATURE AND PRESSURE ON COMBUSTION EFFICIENCY

function of baffle spacing which in turn is an indication of the degree of mixing behind baffles. The pressure term of the correlating parameter of Chapter 8 was expressed to a power <u>n</u> and this exponent varied with baffle spacing. This pressure exponent can also be obtained from the slope of the efficiency versus pressure curve plotted on log-log coordinates. The straight line is probably valid for efficiencies below 90 per cent since one would expect the slope to change as efficiency approached 100 per cent. Data* from several baffle combustors plotted as combustion efficiency versus combustor-inlet pressure (Fig. 10.3-4) indicate that the dependency of efficiency on pressure (slope of the curve) is also a function of baffle spacing. This can be better demonstrated by the table below which gives for the various combustors in Fig. 10.3-4 the corresponding values of D_s, pressure exponent from the correlating curve (Chapter 8), and pressure exponent from the η versus pressure curve (Fig. 10.3-4). It will be noted that the pressure exponents obtained by the two methods are in fair agreement.

Combustor	D_s**	Pressure Exponent Simple - Baffles	Pressure Exponent Slope Curves Fig. 10.3-4
Marquardt 28-inch	2.420	0.26	0.31
Marquardt 20-inch	1.250	0.42	0.44
XPM	1.780	0.34	0.37
UAC 5-inch	2.125	0.30	0.37
UAC 4-inch	2.000	0.32	0.35
Exp.Inc. 2-inch	0.65-1.0	0.5 to 0.6	0.62

*Most of the data for the full-scale engines are taken under conditions of fairly uniform air-fuel distribution.

**The value of D_s is given by the equation below where d_s is the average distance the flame would travel radially outward from a contributing flame holder centerline before meeting another flame front or wall boundary. ΔA is the area over which the flame-holding element is effective and A is the total area of the duct cross section where all the elements are located. In cases where a pilot is present, its area is not included in the cross section.

$$AD_s = \sum_{A=0}^{A=A} d_s \, \Delta A$$

The pressure exponents from the more firmly established η versus pressure curves (greater number of points) show the least difference when compared to those predicted from simple baffles. The actual pressure exponents for the combustors are all slightly greater than would be predicted. Data for the simple baffles were taken under ideal conditions where somewhat less sensitivity to pressure might be expected.

Flame Holder Geometry

The geometric variables in flame holder design are baffle size, shape, number, spacing, blockage, and staggering. As demonstrated below only spacing appears to have a large effect on the over-all combustion efficiency of ramjet engines. Baffle combustors range from simple single flame holders to very complicated network types. In some cases pilots are utilized. A series of tests conducted at NACA [1,9] on a Marquardt 28-inch engine serves to illustrate the effect of baffle spacing and enables a comparison to be made with the results of flame spreading behind simple baffles (Chapter 8).

Figure 10.3-5 shows the effect of a number of geometric variables on the combustion efficiency of the Marquardt engine. The combustors consisted of various sizes and numbers of annular V-gutters connected by radial gutters. A fairly uniform fuel-air distribution existed at the flame holders and the over-all fuel-air ratio of the test was 0.06. The combustion-chamber inlet temperature was 250 degrees Fahrenheit and the inlet pressure was of the order of 15 lb/in^2 absolute. For this particular engine, operating at the indicated fuel-air ratio and inlet condition, the combustion efficiencies are high; therefore, any improvement in efficiency due to change in design will be small.

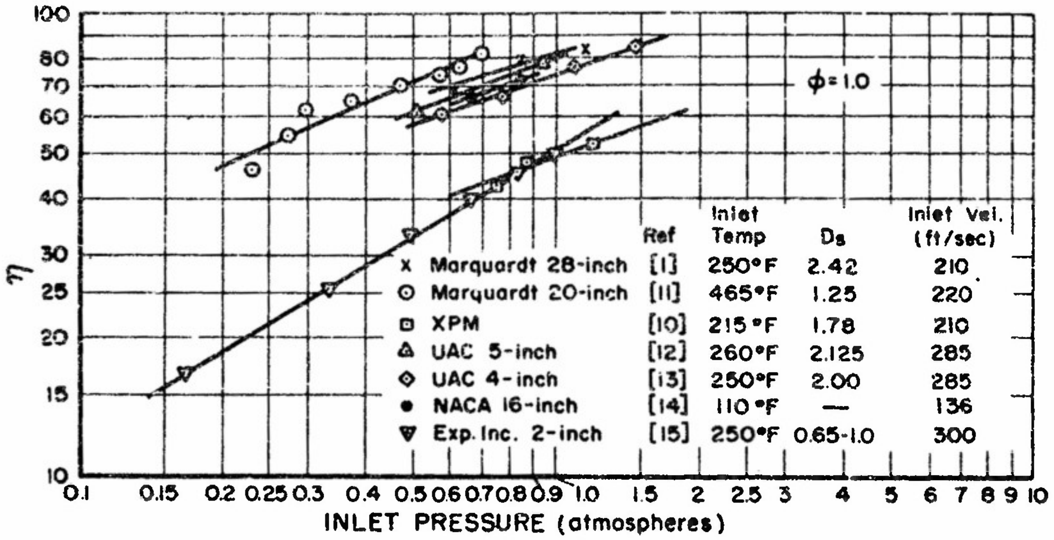

Fig. 10.3-4 EFFECT OF PRESSURE ON COMBUSTION EFFICIENCY OF VARIOUS BAFFLE ENGINES

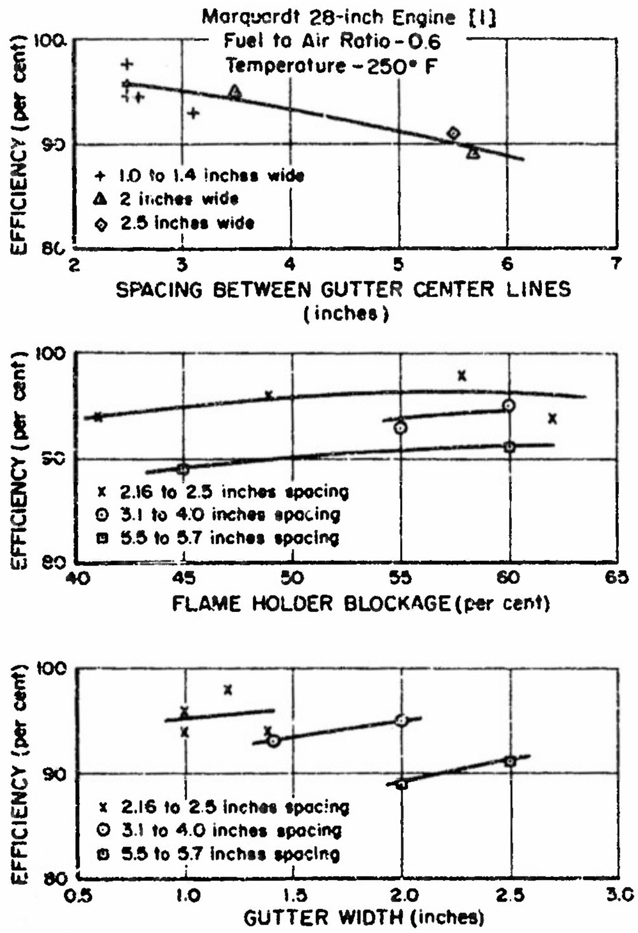

Fig. 10.3-5 EFFECTS OF GEOMETRIC VARIATIONS ON COMBUSTION EFFICIENCY

If a shorter tailpipe were used for these tests (to give lower efficiencies, say of the order of 50 per cent), the changes in design would probably show larger improvements in efficiency due to higher flame-spreading rates in this lower efficiency region.

In Fig. 10.3-5(a), the combustion efficiency is presented as a function of spacing between gutters since it was shown in the flame-spreading correlation (Chapter 8) for simple baffles that the amount of flame spreading is dependent on the distance the flame has to spread from the centerline of one baffle to the centerline of the adjacent baffle or to the wall. The closer the baffles are together, the higher the initial flame spreading. It can be seen that this same effect is also true for the Marquardt engine [Fig. 10.3-5(a)] where higher efficiencies are obtained with closer spaced elements. The flame spreading correlation predicts that given a spacing between gutters of 6 inches and a corresponding combustion efficiency of 87.5 per cent, the combustion efficiency would be of the order of 95 per cent for a new spacing between gutters of 2.5 inches. This predicted result is almost identical to the corresponding point on the faired curve of Fig. 10.3-5(a). The effect of flame-holder blockage and width are shown in Figs. 10.3-5(a) and (b), respectively. Simple baffle tests showed the effects of blockage and baffle size to be small and thus were neglected. Although some effect of gutter width and blockage are shown in this Marquardt engine, general experience with other combustors indicates that efficiency is usually not affected by these variables.

The survey (Appendix I), which reviews a representative group of combustors, shows that probably the most common shape used is the V-gutter. This has been utilized in the form of radial or annular elements. The 16-inch NACA combustor [14] was

tested with a number of complicated shapes, but in general the performance difference between configurations was not significant, and probably matched performance could have been obtained by altering the fuel distribution. From a fabrication standpoint, the elements should be as simple as possible and complicated shapes are only justified when a marked gain in performance can be demonstrated.

The design of a baffle-type combustor for low pressure operation would necessitate the use of a large number of flame holders to give high efficiency and the use of wide baffles to obtain the best stability. The combined effect of trying to hold high efficiency and wide stability limits results in high-blockage combustors. As will be shown in Section 10.5, high blockage gives high drag coefficients but staggering the baffle arrangement helps to reduce this coefficient. A series of tests was conducted at the Applied Physics Laboratory, The Johns Hopkins University [16] to study flame spreading from swept back radial gutters attached to a central pilot. In the course of the experiment, the gutters, which normally extended radially outward from the pilot, were swept back to an angle of 30 degrees with the burner axis. Results are given in the table below.

Effect of Staggering Flame Holders on Combustion Efficiency

Radial Gutters		30-Degree Swept Gutters	
Number of Gutters	η*	Number of Gutters	η
4	45-56	6	34
6	60-69	9	49
14	85-95	14	71

*This spread in combustion efficiency results from changing gutter shape and different types of small mixers on end of pilot.

The width of the gutters was varied with number so that there was a constant blockage of 45 per cent including pilot. There is an indication that, when the elements are swept back or staggered, lower efficiency results. As pointed out before, in cases where drag is an important design consideration, staggering can be used to reduce this loss. Other design changes can then be made to bring the efficiency up to a satisfactory level to meet missile requirements. It has also been found that staggered or swept back elements reduce the range of smooth burning, but there are only very limited data on this observation.

Pilots

The heat release from most pilots used in current baffle-engine designs (Section 10.4) is low compared to the over-all combustor heat release. In general, at the air-fuel ratio for maximum over-all efficiency, the amount of the main-fuel flow to the pilot has been less than 5 per cent. On some very small-scale equipment, higher fractional heat releases were used.

Results obtained by NACA [3,1] on a 28-inch engine with and without a pilot are shown in Fig. 10.3-6 and indicate that slightly lower efficiencies are obtained with the pilot-burner. The difference in performance of the combustors can be in part attributed to other physical differences. It is probable that the effect of fuel-air distribution is the primary cause of these lower efficiencies (see the section on fuel-air ratio and distribution) since the location of the fuel-manifold rings was different for the two configurations; however, smoother operation resulting from use of a pilot could decrease mixing and give a lower efficiency.

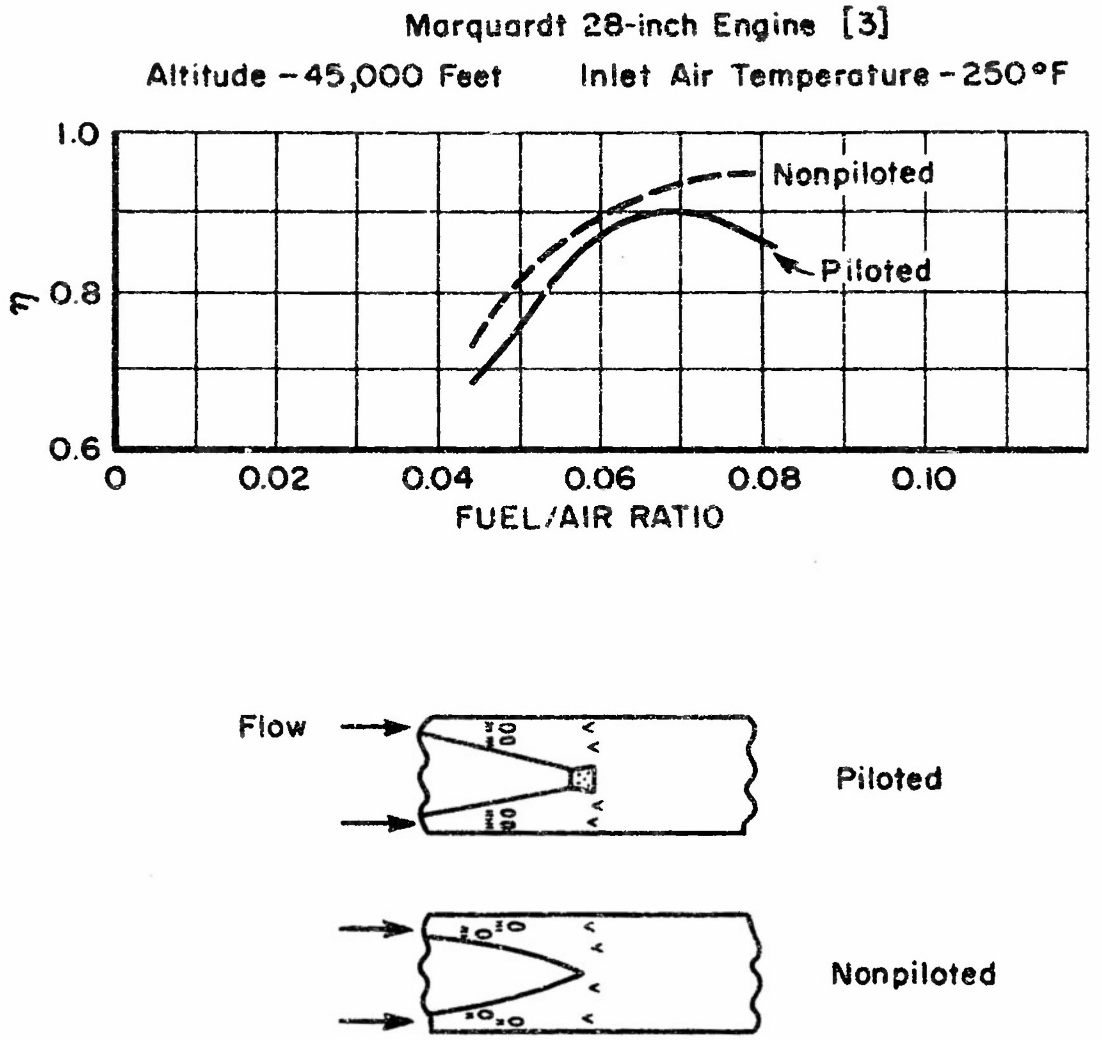

Fig. 10.3-6 EFFECT OF PILOT ON COMBUSTION EFFICIENCY

Improved combustion efficiency was accomplished in the XPM [10] by simultaneous modification of the fuel injector and pilot-burner. The pilot was modified by increasing the heat release. However, since two changes were made at once, it is difficult to judge to what degree the pilot improved the efficiency.

It is fairly obvious that for large-scale combustors, over-all efficiency is not greatly affected by the low heat-release pilots used. If higher heat releases were used as in the Experiment Incorporated 2-inch burner (see Chapter 8 and Section 10.4), then the pilot would be expected to affect the over-all combustion efficiency.

Fuel-Air Ratio and Fuel-Air Distribution

There are a number of ways in which to measure and define "combustion" efficiency. It is important especially in the discussion that follows that a distinction be made between the different definitions of efficiency. Since missile performance is based on the thrust delivered by the engine, the efficiency reported for ramjet engines should be based on thrust efficiency. The exit-stream thrust from the combustion chamber is given by

$$F_{ex} = W_a \, S_a \, \phi(M_{exit})$$

where

W_a = air flow,

S_a = air specific impulse, and

$\phi(M_{exit})$ = ratio of stream thrust to critical stream thrust as a function of Mach number.

Since ramjets operate at a Mach number of 1.0 at the nozzle throat then $\phi\,(M_{exit}) = 1$. The thrust efficiency is obtained by

$$\eta = \frac{\phi_{ideal}}{\phi_{actual}}$$

where

ϕ_{ideal} = equivalence ratio to give measured value of S_a with 100 per cent combustion efficiency and complete mixing,

ϕ_{actual} = combustor over-all equivalence ratio.

If a uniform temperature profile exists, then aside from nozzle losses, the efficiency based on thrust and the chemical efficiency based on heat release or fuel burned are the same. It has been shown [42] that localized complete burning of the fuel in portions of the air stream passing through the combustion chamber sets up nonunidimensional conditions, and if no or partial mixing between streams takes place, the resultant temperature profile can severely reduce the exit thrust compared to that obtained with complete mixing. The efficiency (see Chapter 3) based on thrust would then be lower than the chemical efficiency (based on heat release). This is because the thrust efficiency is obtained by an integrated function of the square root of the exit total temperature profile while the chemical efficiency is obtained by an integrated function of the first power of the exit total temperature profile.

The amount of mixing that takes place between the flame holder and combustion-chamber exit depends partly on the baffle arrangement and tailpipe length. For most combustors with uniform fuel-air distributions, the mixing is sufficient to give

fairly uniform temperature profiles. However, this amount of mixing may not be adequate to produce uniform temperature profiles with nonuniform fuel-air distributions. For this reason there is probably no large difference between thrust and chemical efficiency for a unit with a uniform fuel-air distribution and fairly high efficiency; depending upon the degree of mixing, there may be large differences with a nonuniform fuel-air distribution even though combustion efficiency is high.

The effect of air-fuel ratio on flame spreading behind simple baffles (Chapter 8) in a homogeneous vaporized air-fuel mixture is similar to the change in laminar burning velocity over the same air-fuel ratio range. That is, efficiency is a maximum (at a given distance downstream from the baffle) for a near stoichiometric mixture ratio, and falls off with richer or leaner mixtures. General experience with full-scale ramjet combustors has indicated that a peak always exists in combustion efficiency as air-fuel ratio varies, provided that the fuel distribution does not change drastically with air-fuel ratio. If the distribution is uniform, this peak lies near stoichiometric ratios. Examples from actual combustors may be found in References [17,18,19]. If, as is frequently the case, the distribution is rich near the baffles and lean elsewhere, the peak will occur on the lean side.

The effect of nonuniform distribution on chemical efficiency is to give peak efficiencies which are generally lower than the peak efficiency for uniform distribution. For a given tailpipe length, the uniform distribution has a maximum efficiency at a stoichiometric mixture. With a nonuniform distribution at its maximum efficiency point, there are regions in which the local mixture is either richer or leaner than stoichiometric. Therefore in the same tailpipe length, lower local chemical efficiencies will occur because of the lower flame velocities,

thus giving a lower over-all chemical efficiency. Examples of some of the above effects of fuel distribution on combustion efficiency are shown by measurements made on the Y-gutter combustor of Fig. 10.2-7. For constant total fuel and air rates to give a near stoichiometric air-fuel mixture, and with varying injection needle position, various fuel-distribution curves (measured at the gutter) were established; the extremes are illustrated in Fig. 10.3-7. For the dotted curve, representing a fairly flat distribution with only moderate concentration gradients near the wall, the measured air specific impulse (S_a) was 155.7 lb/lb/sec. For the solid curve, representing severe concentration gradients, (quite rich in the center of the duct and very lean near the walls), the observed S_a was 144.8. With fuel-needle positions giving distributions intermediate between the extreme curves shown, the measured air specific impulses were similarly intermediate. These variations in S_a, it should be recalled, were all obtained near a stoichiometric over-all air-fuel ratio.

The results obtained for the Y-gutter give quantitative evidence of the effect of fuel distribution on combustion efficiency and emphasize the desirability of using flat, and if possible, homogeneous mixtures to maximize the efficiency. This is further demonstrated in data on a large-scale engine [1] which are presented in Fig. 10.3-8. For this 28-inch combustor with annular rings for flame holders, two fuel-distribution patterns (uniform type or high concentration type) were obtained by a special fuel-injection arrangement. At a fuel-air ratio of 0.045, the uniform distribution had a higher efficiency than the high concentration distribution.

At lean over-all air-fuel ratios the value of thrust efficiency obtained with a nonuniform distribution can vary widely, depending on a number of considerations. If there is

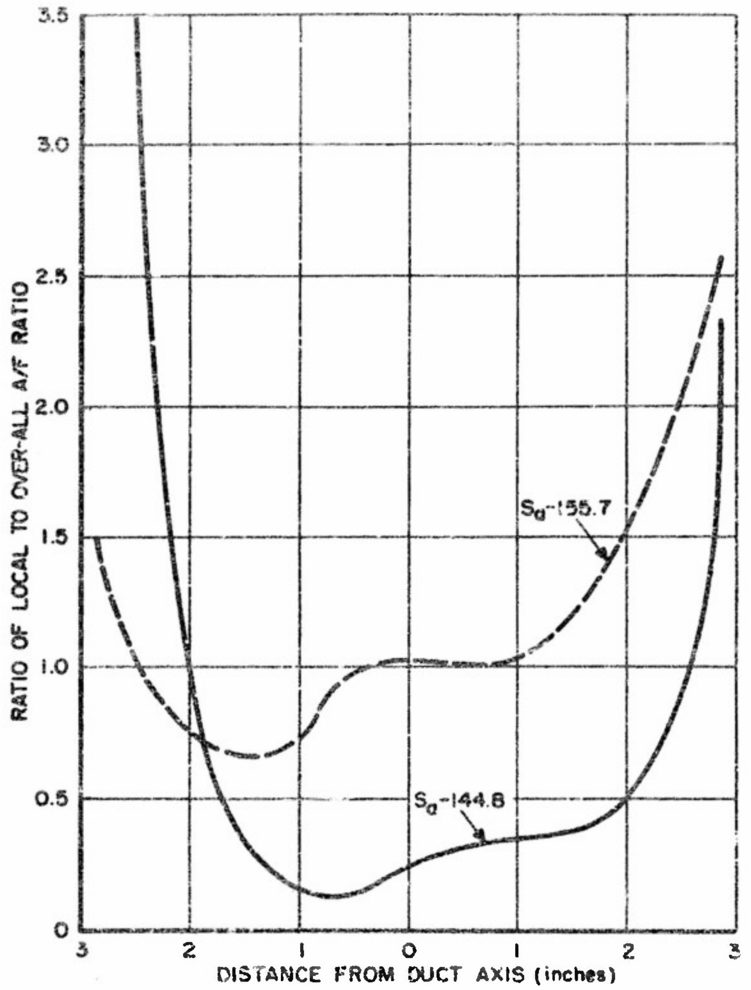

Fig. 10.3-7 FUEL DISTRIBUTION CURVES FOR THE Y-GUTTER COMBUSTOR (AT EQUAL OVER-ALL AIR-FUEL RATIOS)

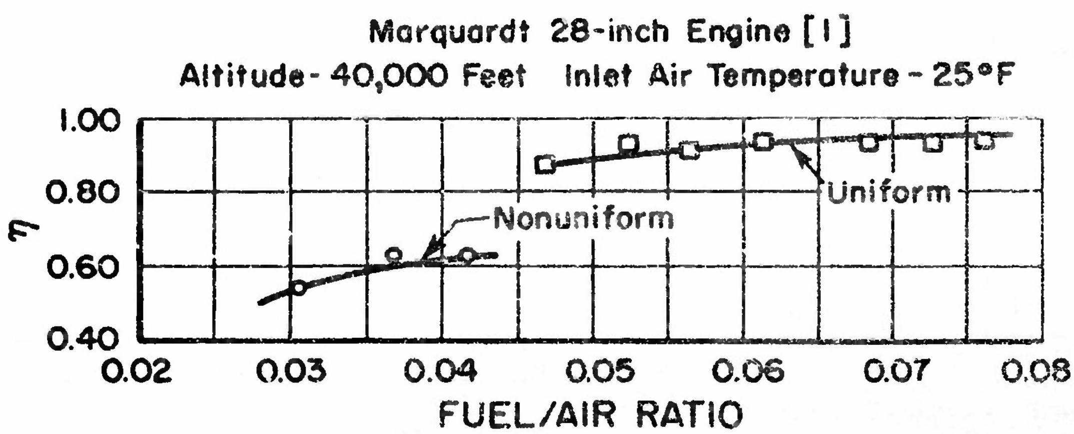

Fig. 10.3-8 EFFECT OF AIR-FUEL RATIO ON COMBUSTION EFFICIENCY

perfect mixing with corresponding uniform exit temperature profiles at these lean over-all mixtures, one may gain by burning a portion of the air as a locally rich mixture and then mixing with the remaining air. The distance required to burn a relatively rich mixture (near-stoichiometric) to the same chemical efficiency is less than required to burn a very lean mixture. Therefore the total distance to burn and then mix hot and cold gases may be less than to burn the over-all lean mixture. Although this principle has been applied mainly to can designs where there is better control of these primary and secondary streams, experimental work has been carried on at NACA [39,40] with baffles and control sleeves. This will be discussed more fully later. As will be shown in the examples below, for typical baffle combustors, the thrust efficiencies at lean over-all air-fuel mixtures and nonuniform distribution are almost always lower than those obtained with a uniform distribution at the same air-fuel ratio. This leads one to suspect the mixing of the gases downstream of the baffle. Figure 10.3-9 shows the theoretical thrust efficiencies that one would expect for various percentages of the mixture at a uniform high temperature. For example, if 40 per cent of the mixture is burned at stoichiometric (over-all $\phi = 0.4$) and does not mix with the surrounding air, then the efficiency based on S_a would be 66 per cent. An illustration of this nonmixing in actual combustors is given in Fig. 10.3-10 for a United Aircraft Corporation multi-unit (see survey in Appendix). If the mixing were perfect then one would expect no dropping off of the efficiency as the units were cut out. The dashed line through the data connects the theoretical thrust-efficiency points calculated as if the individual units operating were burning completely at a $\phi = 1.0$ and not mixed with the air from the cut-out units. It may be seen that this condition approximates closely the actual data points.

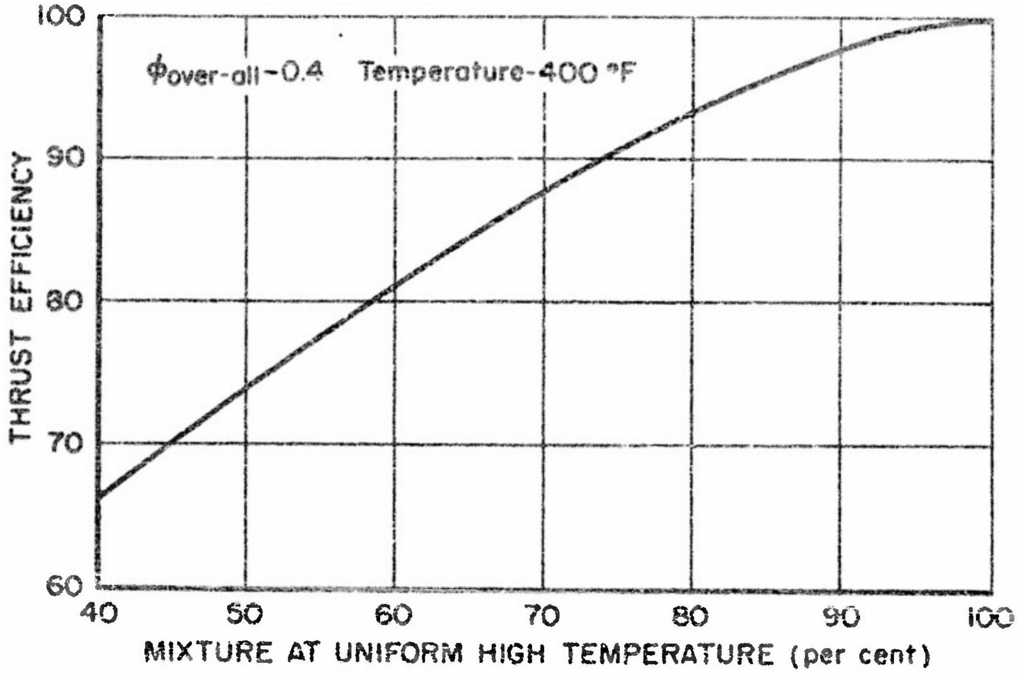

Fig. 10.3-9 EFFECTS OF VARIOUS DEGREES OF MIXING ON THE OVER-ALL THRUST EFFICIENCY

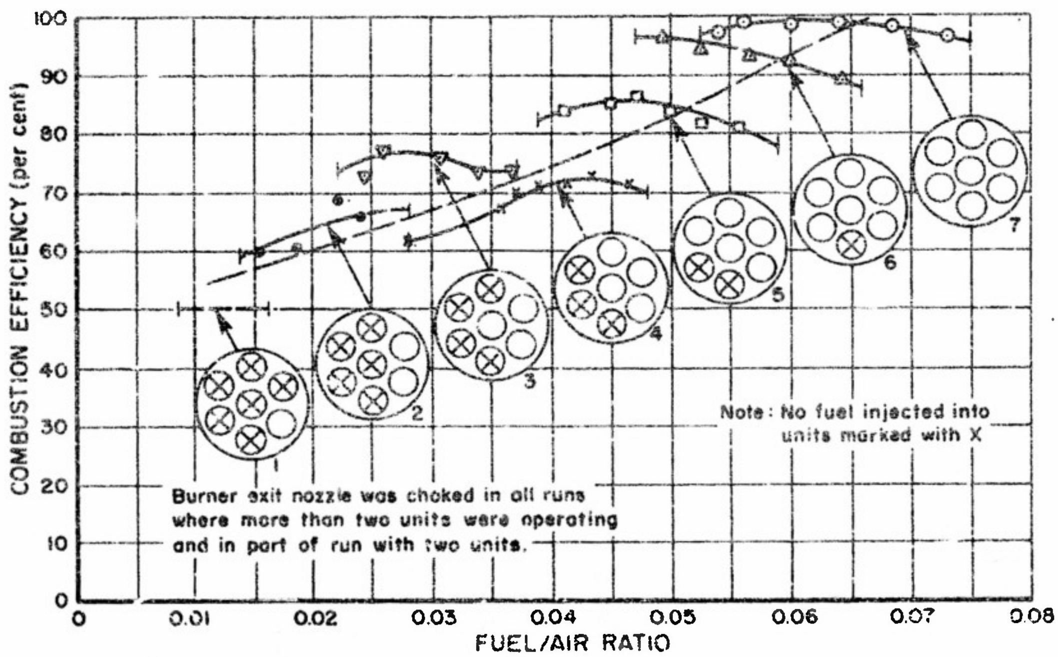

Fig. 10.3-10 PERFORMANCE OF MULTI-UNIT BURNER WITH VARIOUS NUMBER OF UNITS OPERATING

High efficiency at lean over-all fuel-air ratios with baffle-type combustors has been achieved in certain models of the NACA 16- and 20-inch engines [39,40]. In the 16-inch unit a cylindrical sleeve, which captured 20 per cent of the total engine air flow, ducted the air past a pilot into a primary combustion zone. Swept-back V-gutters extended radially from the central pilot to the inner wall of the cylindrical sleeve. Following the cylindrical sleeve was a conical section or shield on which, at the downstream end, were attached swept-back V-gutters, which extended radially to the combustion-chamber wall. Fuel could be injected to either inner or outer zones. For lean operation, this design provides control of the fuel-air mixture and also provides control of the mixing of the burned and unburned gases. That is, at lean air-fuel ratios, combustion is maintained only in the primary zone and dilution with secondary air takes place downstream of the shielded region. For rich operation, fuel is also injected into the secondary stream. The tailpipe used in this 16-inch engine was 90 inches in length so that a sufficient distance was allowed for mixing. The normal tailpipe length used in most baffle combustors is about 50 inches. At the operating conditions of this test, a combustion-efficiency level of 90 per cent or greater was obtained over the range of fuel-air ratios from 0.010 to 0.045. In the 20-inch engine with a control sleeve, three 3-inch-wide gutters extended radially from the downstream end of the pilot burner to the combustion chamber wall. Two 1-inch-wide annular V-gutters interconnected the radial gutters. The cylindrical control sleeve extended from between the fuel-injection manifolds downstream to the flame holders. Fuel could be injected to either side of the control sleeve. Two tailpipe lengths (48 and 77 inches) were used in these tests. For the baffle configuration without the control

sleeve, the combustion efficiency fell off rapidly at fuel-air ratios leaner than 0.04 and the lean stability limit was at a fuel-air ratio of 0.0275. At the same operating condition, but with the control sleeve, a fairly high efficiency was obtained until lean blow-out at a fuel-air ratio of 0.018. The highest efficiency was obtained near over-all stoichiometric mixtures when the fuel was injected to both primary and secondary streams. These tests illustrate that control of burning and mixing can be accomplished in baffle-type combustors in order to obtain high efficiencies at lean over-all fuel-air ratios but at the cost of added weight, drag, and complexity.

One can now appreciate that predicting the thrust efficiency of combustors with nonuniform fuel distributions and different degrees of mixing is very difficult. However, methods will be outlined here from which one can calculate the efficiency for conditions of mixed and nonmixed streams so the actual efficiency will be bracketed. This may be done by dividing the combustor cross-section into small sections (annuli in the case of cylindrical ducts) and treating each of these small area sections as individual combustors. The fuel gradient across each section is averaged to give a uniform air-fuel distribution and using the D_s value for the flame holder in that section, the efficiency at the tailpipe exit is computed according to the flame spreading correlation of Chapter 8. If the mixing is complete, then one can weigh the efficiencies by the fraction of the fuel in the sections taken and obtain an over-all thrust efficiency. For the nonmixing case an over-all effective air specific impulse in a choking burner can be computed by the following equation

$$S_{a_{eff}} = \sum_{n=0}^{n=I} S_{a_n} \quad n$$

where

$$n = \frac{\text{mass flow in section}}{\text{total mass flow}} ,$$

S_{a_n} = air specific impulse at an equivalence ratio of $\eta_n \phi_{n_{average}}$,

η_n = chemical efficiency of section, and

$\phi_{n_{average}}$ = average input equivalence ratio of section.

The over-all thrust efficiency can now be obtained

$$\eta_{over-all} = \frac{\phi_{eff}}{\phi_{over-all}} ,$$

where

ϕ_{eff} = equivalence ratio to give $S_{a_{eff}}$,

$\phi_{over-all}$ = combustor over-all equivalence ratio.

The above method of obtaining the effective specific impulse does not take into account the change in Mach number across the exit and assumes constant specific heats. One now has the values of efficiency calculated for the mixed and nonmixed conditions. The actual thrust efficiency is generally between these two values but at the present writing there is no way to further fix the predicted points. From the data given for the UAC multi-unit, one might choose the predicted point to be closer to the nonmixing condition. If long tailpipes are used such as in the NACA 16-inch engine [39], then the efficiency will be closer to the mixed condition.

Fuel Vaporization and Fuel Type

Not only is the actual air-fuel ratio in the region of the flame holder important, but the degree of fuel vaporization in that region is also important. Test data are available to point up this fact. In one such test [20], a 1-1/2-inch pilot, with its own fuel-injection system was mounted in a 6-inch duct and a certain amount of the total air flowing (termed the per cent pilot) diverted through the pilot and burned almost completely. The products of combustion exhausted into the duct through which an unburned combustible mixture was flowing. Measurements were made, 18 inches downstream of the pilot exit, of the rate at which the flame had spread from the pilot exit throughout the duct. Conditions in this case were a pressure of one atmosphere, a mixture velocity of 200 ft/sec and an inlet-air temperature of 250 degrees Fahrenheit. The over-all air-fuel ratio was maintained at 18 to 1. For the various per cent pilots and various pilot air-fuel ratios, a comparison was made of flame spreading for three types of main-duct fuel injection. The first type employed a homogeneous vaporized naphtha feed. In the second type, liquid naphtha was injected ten inches upstream of the pilot outlet and in the third diesel oil was injected at the same point. The primary difference in these types of injection is obviously the degree of vaporization of fuel attained - from 100 per cent in the first type to a negligible amount in the third. Some of the results are tabulated in the table below.

		Per Cent Main Duct Fuel Burned		
Per Cent Pilot	Pilot A/F	Homogeneous Vap. Naphtha	Liquid Naphtha	Diesel Oil
11	14.2	57	50	35
11	16.0	53	47	18
7	14.2	-	42	25
7	18.0	-	39	22

The importance of fuel vaporization on combustion efficiency is apparent from the data shown in the preceding table. The performance of large-scale ramjet engines follows the same trend observed in the preceding discussion. An example of this may be found in Reference [2] for a 28-inch combustor in which normal heptane and diesel oil were used as fuel. The results are plotted in Fig. 10.3-11. For the range of fuel-air ratios investigated, the combustion efficiency was about 40 per cent lower with diesel oil than with normal heptane. It appears from the flame-spreading correlation (Chapter 8) that approximately one foot of extra tailpipe length would be required to bring the efficiency of the diesel system up to that obtained with normal heptane.

Fuel type (see flame spreading, correlation, Chapter 8) also affects the efficiencies of baffle-type combustors. Results from an Experiment Incorporated 2-inch burner [15], correlate impulse efficiency with laminar burning velocity. Various fuels with burning velocities ranging from 38 to 175 cm/sec were tested and progressively higher impulse efficiencies were obtained with progressively higher burning-velocity fuels.

Turbulence

Data from simple baffle experiments (Chapter 8) indicate that the turbulence of the entering air stream affects the flame spreading in the region immediately downstream of the baffle with small-scale turbulence giving higher initial-burning rates. Also, closely spaced grids appear to break up any large-scale turbulence and the system operates on a higher efficiency level than one would predict from the inlet-air turbulence.

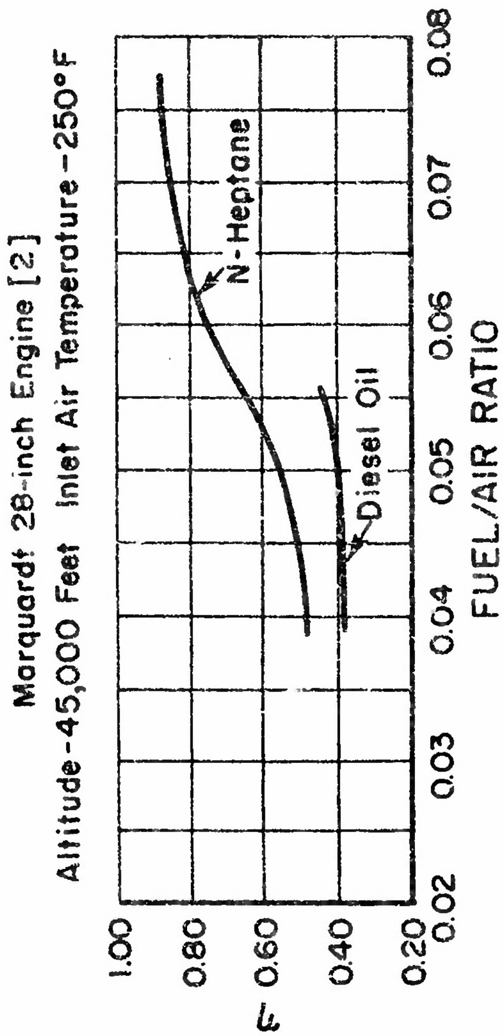

Fig. 10.3-11 EFFECTS OF FUEL-PHASE DISTRIBUTIONS ON COMBUSTION EFFICIENCY

It was pointed out that factors other than turbulence may have contributed to these changes in burning rate but that they have not yet been isolated. Application of the above findings have not been made to full-scale engines at the time of this writing.

Comparison of Predicted and Actual Tailpipe Lengths

In order to demonstrate how effectively the tailpipes of baffle-type combustors are being utilized, a comparison can be made between the actual combustors' tailpipe length and the length predicted from the flame-spreading correlation for simple baffles (Chapter 8). This is shown in Table 10.3-1 where, for a number of combustors, the predicted tailpipe length is computed from the flame-spreading correlation. Since the air-fuel distributions of nearly all these combustors were uniform, there is probably no large effect of mixing on combustion efficiency. It may be seen that these full-scale combustors require more tailpipe length than predicted. It is felt that the reason for this can be found in the inlet air-condition, fuel type, fuel-injection system, and general burning characteristics. In the 20-inch Marquardt engine, JP-3 (a very wide boiling range fuel) was introduced at a point 15-1/2 inches upstream from the flame spreaders using downstream-injection nozzles. Even at the high inlet-air temperature of operation, only part of the fuel would be vaporized when reaching the flame holders because of the downstream type injection and the short distance between the nozzles and flame holder. Therefore, a longer tailpipe length is needed in relationship to a vaporized system. However, as pointed out previously, only about one foot of additional tailpipe length is needed to burn a vaporized fuel as compared to an unvaporized fuel. The extra length requirement of the 20-inch Marquardt

TABLE 10.3-1

Predicted Tailpipe Length Computed from Flame-Spreading Correlation

Combustor	Combustor Tailpipe Length (inches)	D_s	Pressure in Atmospheres	Temperature (^oR)	Velocity (ft/sec)	$\phi_{over\text{-}all}$	η_c	Combustor Correlating Parameter	Simple Baffle Correlating Parameter	Combustor Additional Tailpipe Length (inches)
Marquardt 20-inch	55.5	1.25	0.275	925	220	1.0	54.4	1.73	1.08	23.4
Marquardt 28-inch	57.0	2.42	0.619	710	210	1.0	68.6	1.585	1.23	12.8
XPM	63.0	1.78	0.805	770	231	1.0	52.0	2.00	1.058	34.0
UAC 4-inch	40.0	2.0	0.582	743	283	1.0	61.0	1.184	1.145	1.4
UAC 14-1/2-inch	82.0	7.0	2.510	735	246	0.94	87.0	1.72	1.55	5.0

engine is probably due to nonhomogeneity of the fuel across the combustion chamber. The 28-inch Marquardt engine and XPM are similar in baffle spacing and general over-all arrangement; however, the units use different fuel and have different types of fuel-injection system. The Marquardt engine uses heptane fuel which is injected through contra-stream nozzle; while the XPM uses JP-1 fuel injected through contra-stream tubes to which "Tee" spreaders are attached. Another slight difference is that the Marquardt injector is located 37 inches upstream of the flame holder, while this distance in the XPM is 30 inches. Considering the fuel-injector location, type injector, and fuel type, one would expect better vaporization of the fuel in the Marquardt engine. The preceding table shows that the additional tailpipe length required for the 28-inch Marquardt engine and XPM is about 13 inches and 34 inches, respectively. About two feet of combustion chamber length is saved in the Marquardt engine compared to XPM. All of this extra tailpipe in the XPM cannot be accounted for just by the differences in fuel distribution and fuel vaporization of the two engines. The air flow at the diffuser exit of the XPM is highly turbulent. This, coupled with the low pressure, dribbler-type fuel injector, probably gives a poor fuel distribution in the sense that, although an air-fuel traverse would show a smooth distribution on a time average basis, the fuel combines with the air in the form of random rich and lean pockets. This unstable condition would require more tailpipe length to obtain a given efficiency as compared to a better mixed system. A further illustration of complete combustors is indicated by the 4-inch United Aircraft Corporation engine. Here the gasoline is injected radially into the air stream at the diffuser entrance through wall nozzles. Then vortex generators help mix the fuel and air together as they pass through the 39-inch

"mixing section". For this configuration the calculated parameter number falls within the accuracy of the flame-spreading correlation. The fuel for this case was probably completely vaporized.

In comparing calculated flame-spreading parameter from the 4- and 14-1/2-inch United Aircraft Corporation combustors, it was found that they both fall very close to the predicted value for the same efficiency. The fuel in both cases can be assumed to be completely vaporized when reaching the flame holders. The values of D_s were taken as the combustion chamber radius although one configuration had an annular wall-type baffle and the others a center baffle.

Design Recommendations for Efficiency

Again it should be stressed that a clean aerodynamic diffuser is essential, not only for maximum stability, but also for maximum efficiency. For the same over-all efficiency the additional tailpipe length requirement of the XPM (see section on comparison of tailpipe lengths) due to the instability of the diffuser is probably of the order of one foot compared to a similar combustor with a clean diffuser.

Although the combustion chamber inlet conditions affect flame spreading behind baffles, these conditions are fixed by missile requirements and not by the engine designer. To insure a good design from an efficiency standpoint, the baffle elements should be small and very close together. However, this is opposite to design principles for good stability. In order to have an extended stability range, a fuel distribution with large concentration gradients is required but, as has been shown, such gradients usually make for poor efficiency. Conversely, maximum

efficiency requires uniform distribution which in turn makes for a narrow stability range. The designer must weigh the importance of these conflicting trends in order to arrive at an optimum design.

The placement of the flame-holding elements is usually as close to the diffuser exit as possible. The fuel injectors and sometimes the forward section of the pilot are located further upstream in the subsonic portion of the diffuser. This is helpful in reducing the missile length, but care should be taken because high blockages in this region of high velocity in the diffuser may produce excessive drag.

The flame-spreading correlation (Chapter 8) can be used directly to predict the efficiency of full-scale combustors, provided the fuel is completely vaporized and uniformly distributed. In cases of partially vaporized or unvaporized fuel present at the flame holder station, additional tailpipe lengths would be required to bring the efficiency up to the desired level. The estimated additional length is about one foot, comparing an unvaporized to a vaporized system. In cases where a non-uniform air-fuel distribution exists, the methods outlined in the section on fuel-air ratio and distribution may be used to calculate thrust efficiency of unmixed or mixed exhaust gases.

It appears that the poor mixing of the gases downstream from the baffles is a limitation in obtaining the maximum thrust efficiency under certain conditions. A method of increasing this mixing has been demonstrated by tests conducted by NACA [38] in a 5-inch-diameter ramjet. Flame immersed mechanical mixing blades were placed downstream from the main flame holder. The combustion efficiency measured at the exit of a 90-inch tailpipe showed improved efficiency over a combustor configuration without mixers.

10.4 PILOTS FOR BAFFLE COMBUSTORS

As shown in the section on baffle size and inlet-air state, the stability limits of a given baffle configuration can be extended by the use of stable pilots connected to the baffles. The pilots used in baffle-type combustors have had a rather low heat release per unit area and in general no appreciable effect on combustion efficiency was found. Chapter 11 treats in detail the design of pilots, with emphasis placed on the higher heat release can-type pilot which may be of more significance in future designs. All pilots have their own fuel injection system, but some designs have a separate oxygen supply. The method of controlling the pilot fuel varies in the different designs. Some pilots are supplied with fuel at a constant percentage of the main fuel, while other designs attempt to hold a constant pilot air-fuel ratio. With the former method, the pilot fuel flow is controlled by the main fuel-control meter while the latter method requires a separate control meter. The discussion that follows is based on the pilots which have been incorporated into past designs. It might be mentioned that a large baffle, to which smaller baffles are attached, may act as a pilot even though there is no separate fuel supplied to the large baffle. The extended stability of the large baffle compared to the smaller elements will allow piloting of the smaller elements beyond their normal stability range.

Central Pilots - Vortex and Swirl Vane

The most frequently used pilot is the circular-exit type that is mounted in the center of the duct and to which are attached connecting gutters from the main flame holding elements.

In some cases radial gutters from the pilot are the main flame holders. This centrally located pilot is ideal for a missile with an innerbody in that the pilot can be faired into the downstream end of the innerbody. On the larger-scale ramjets surveyed (16 to 28 inches in diameter), it was found that the pilot-fuel system consisted of spray nozzles mounted in the center (spraying aft) of the upstream end of the pilot (Fig. 10.4-1). Air to be mixed with the fuel was introduced in two different manners. In the first type [Fig. 10.4-1(a)], air is admitted to the pilot through a swirl plate which incorporates radial louvers pushed from the surface to form flap-type openings for admission of a swirling primary-pilot air supply at the upper end of the pilot. Additional air is admitted to the pilot through holes in the pilot skirt. The air contains some fuel because the main fuel injectors are located upstream of the pilot. The concentrations of air and fuel entering the pilot depend on the fuel-air distribution near the innerbody wall. In the second pilot [Fig. 10.4-1(b)], an air scoop is located in the diffuser upstream of the main fuel injectors and directs air through tubes to the pilot. Air is discharged into the pilot through angular nozzles which give it a swirl motion.

Table 10.4-1 on the following page contains a listing of some existing engines and a description of their pilots. It is noted that in most cases the per cent of the total fuel injected (also indicating per cent pilot heat release) into the pilots is low. In one design, the Marquardt 28-inch, the pilot air-fuel ratio was held constant while the main fuel was varied. This gave from 2 to 11 per cent of the main fuel flow with the higher pilot fuel flow occurring during lean over-all air-fuel operation. A constant air-fuel ratio pilot is useful in further extending the lean limit over that obtained with a constant percentage of total fuel flow pilot in that it produces

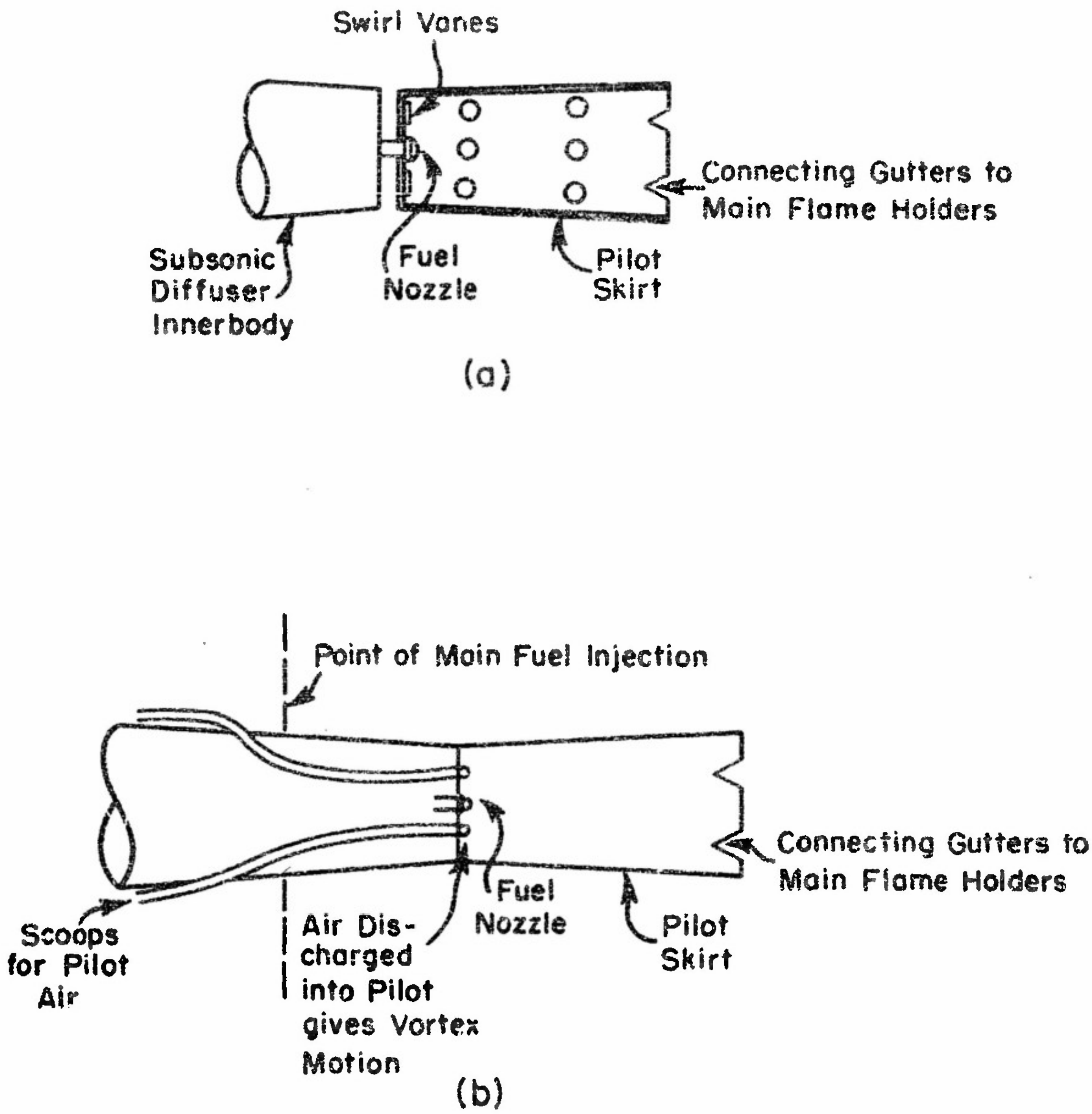

Fig. 10.4-1 TYPES OF PILOTS

TABLE 10.4-1

Pilots in Baffle-Type Engines

Combustor	Reference	Engine Diameter (inches)	Pilot Type	Blockage	Length	Exit Diameter (inches)	Fuel	Per Cent Total Fuel
RTV	24	18	Vortex	15.6	18	7	Same as main	1
XPM	10	28	Vortex	12.7	-	10	Same as main	1
XPM (modified)	10	28	Swirl	12.7	-	10	Same as main	1
Marquardt 28-inch	3	28	Swirl	7.8	4.4	7.8	Same as main	2 to 11
Marquardt 20-inch	11	20	Swirl	9.0	-	6.0	Same as main	-
NACA 16-inch	14	16	Vortex	14.0	10.3	6.0	Propylene oxide	5

a richer pilot at the leaner over-all air-fuel ratios. The vortex-type pilots generally have a smaller heat release compared to the swirl-vane type. Modification [10] of the XPM piloting system was made by replacing the vortex pilot with a swirl-vane type in order to obtain a higher heat release. The pilot blockage ranges from about 8 to 15 per cent of the combustion chamber full area while the total blockage of the pilot and main flame holder was as high as 60 per cent.

Oxygen-Hydrogen Pilots

The pilots discussed in the preceding section are almost exclusively used in large-scale application. Smaller-scale equipment (up to 6 inches) has demonstrated that oxygen and hydrogen can be used very effectively for piloting. One such burner is the Experiment Incorporated 2-inch unit with a 3/4-inch base diameter cone to which were attached, at the downstream end, four 1/4-inch-wide V-gutters at intervals of 90 degrees around the cone. Oxygen and hydrogen were fed inside the central cone. Results from this combustor (Chapter 8) showed that when the pilot heat release was increased (10, 15, and 20 per cent pilots), the over-all efficiency increased. However, the change in over-all efficiency in going to higher pilot heats was greater than one would normally expect, and it appeared that without a large pilot, overmixing was taking place downstream of the baffles with some quenching. This unit would not operate without some degree of piloting. These tests show that in this very small-scale equipment, a pilot is necessary for operation and helps in obtaining better efficiencies.

Combustors designed around oxygen-hydrogen piloted elements have been investigated by the United Aircraft Corporation [12,13]. Small "units" which are complete engines in themselves

are clustered to make up large combustors of different diameters. This combustor is described in detail in Appendix I. These "units" consist of a cylindrical chamber with one annular wall baffle which, in addition to the main upstream fuel injection, was fed by oxygen and hydrogen pilots. Inside this annular baffle are two oxygen-hydrogen pilot-flame injectors spaced 180 degrees apart and mounted flush with the combustion-chamber wall. The pilot flame was introduced under the baffle and tangential to the inner wall of the combustion chamber. Weight flows of oxygen and hydrogen were up to one per cent by weight of the stoichiometric main-fuel flow. The "units" did not require piloting for operation at high pressures, but pilots were needed for low pressure conditions.

10.5 COMBUSTOR DRAG

As shown in Chapter 3, the drag of the combustor parts (this includes baffles, fuel-injector system, supporting struts, etc.) has an important effect on the over-all thrust efficiency. For example, in the open tailpipe Cobra* ramjet under spillover conditions, a two-fold increase in the drag coefficient** of 2.0 has about the same effect as changing S_a from 150 to 130 or changing combustion efficiency from 80 to 60 per cent. The change in net thrust with drag will vary for different over-all ramjet designs. In general, the smaller the exit nozzle, the less effect a given change in drag coefficient has on thrust. For a proposed configuration of the Triton missile with a 45 per cent exit nozzle, an increase in the drag coefficient of 1.0 will result in a decrease in thrust efficiency of only about one per cent.

As mentioned above, the drag of the over-all combustor includes baffles, fuel injectors, fuel manifolds, struts, fastenings, etc. Most of the discussion to follow will be devoted to the flame spreading elements themselves since in most

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*The Cobra test missile designed for flight at Mach 1.6 has a 6-inch-diameter combustion chamber using radial gutters for flame holders. The combustor drag is 2.0.

**The drag coefficient is defined as $C_D = \frac{F}{Aq}$

where

F = drag force,

A = combustion chamber full area, and

q = dynamic pressure based on combustion chamber full area.

cases they are the main contribution to combustor drag. However, with certain designs and locations of the fuel-injector system, this may not be true. To insure vaporization of the fuel, it should be injected as far upstream of the flame holders as possible, but this means locating the injection system in the high velocity region of the subsonic diffuser. In this location, the drag force on an injection system mounted in the air stream would be greater than if it were located in the combustion chamber full area. On the other hand, if it were located in the combustion chamber entrance, (with the flame holder downstream still further) a longer tailpipe would be needed to obtain the same combustor performance. In general the drag of the fuel injectors can be calculated using the appropriate drag coefficients for the various parts and taking into account the momentum of the injected fuel.

Drag in baffle-type combustors is largely determined by the flame-holder blockage; however, combustion efficiency and flame stability are also related to blockage. The rate of flame spreading is nearly independent of blockage for a given number of baffles but increases markedly with number of baffles so the tendency is to increase blockage by putting in more baffles. The stability criterion [45] indicates that an optimum baffle blockage occurs when the ratio of baffle area to gas velocity past the baffle is a maximum. Since this optimum blockage is of the order of 50 per cent, no gains in stability would be predicted for higher blockages. Unless higher efficiencies are required (at the expense of stability), the maximum blockage for the baffle elements apparently should be of the order of 50 per cent.

The total drag force on the type of baffle used in ramjet engines results largely from pressure variation over the surface of the baffle. The drag on the baffle will then be dependent on

its shape which may be in the form of gutters, flat plates, cones or similar elements. In the application of baffles to ramjet design, V-gutters are used most extensively because of their ease of fabrication and structural rigidity. Experimental drag data [25,26,5] are available for V-gutters, cones, and grids under burning and cold flow conditions. This information may be broken down into two general groups. The first is single-plane baffles in which all elements are in a single plane normal to the direction of air flow. The second is staggered baffles in which elements have axial spacing. The staggered baffle arrangement represents an attempt to reduce the over-all drag.

Drag characteristics of baffles are illustrated by data taken at the Esso Laboratory [5] on V-gutter-type baffles mounted in a 5-inch by 9-inch rectangular duct. The drag was determined from a measurement of the pressure distribution along the upstream and downstream surface of a 2-1/4-inch-wide gutter. This was accomplished by a series of static pressure taps located in the wall of the gutter. Typical measured burning and cold flow pressure distributions are shown in Fig. 10.5-1. The upstream static pressure decreases from the leading edge to the trailing edge of the gutter because of the increase in velocity (decrease in area). The downstream or base static pressure is fairly uniform and may be considered constant. No appreciable change in the shape of the pressure distribution curves, between burning and cold flow conditions, was noted.

Single-Plane Baffles

Figure 10.5-2 is taken from [3] and shows the effect of velocity and blockage on the drag of single-plane baffles. As shown in this figure, no change in drag coefficient, C_{D_1}, (see

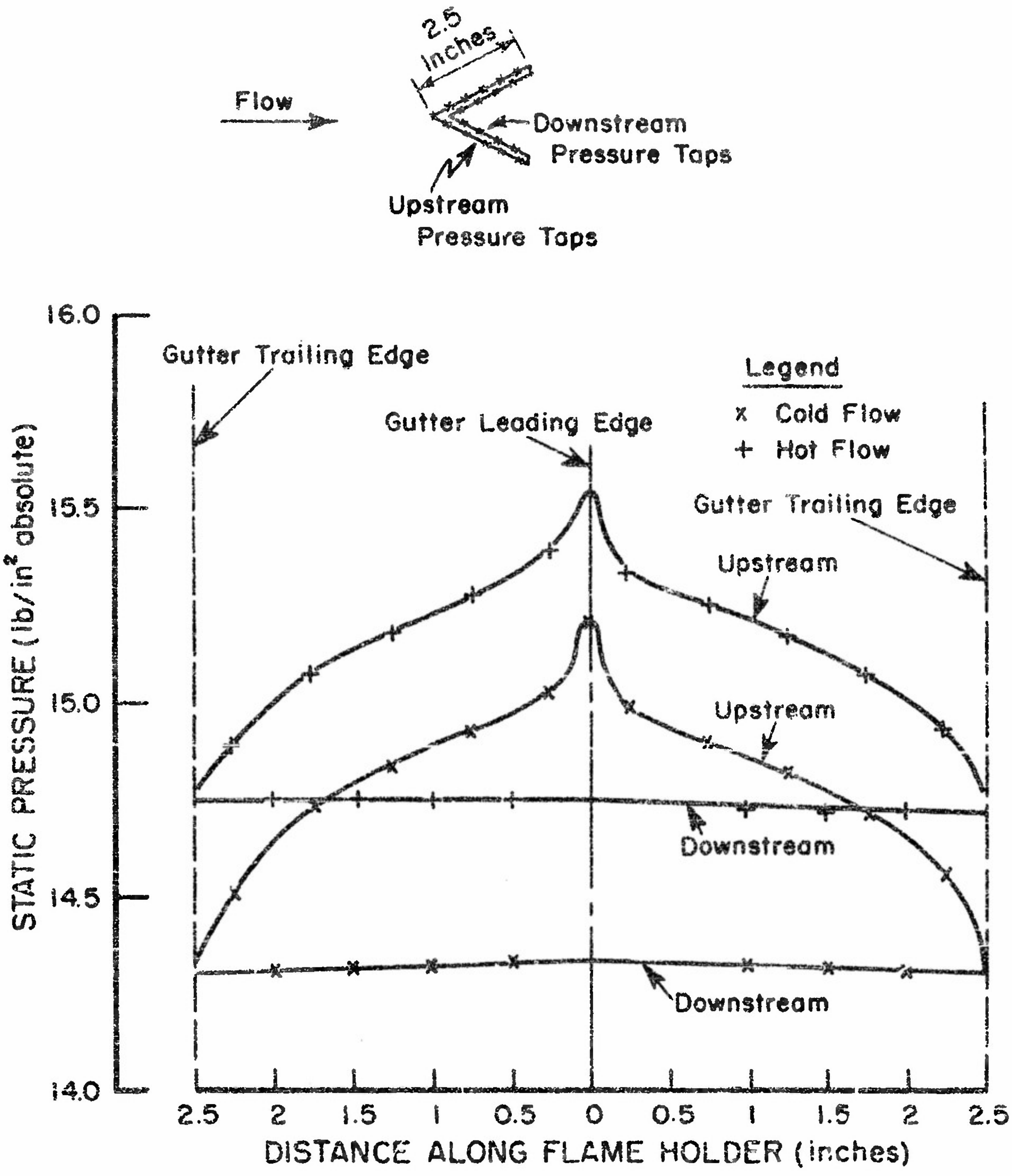


Fig. 10.5-1 TYPICAL HOT AND COLD FLOW DISTRIBUTIONS OVER V-GUTTER FLAME HOLDER

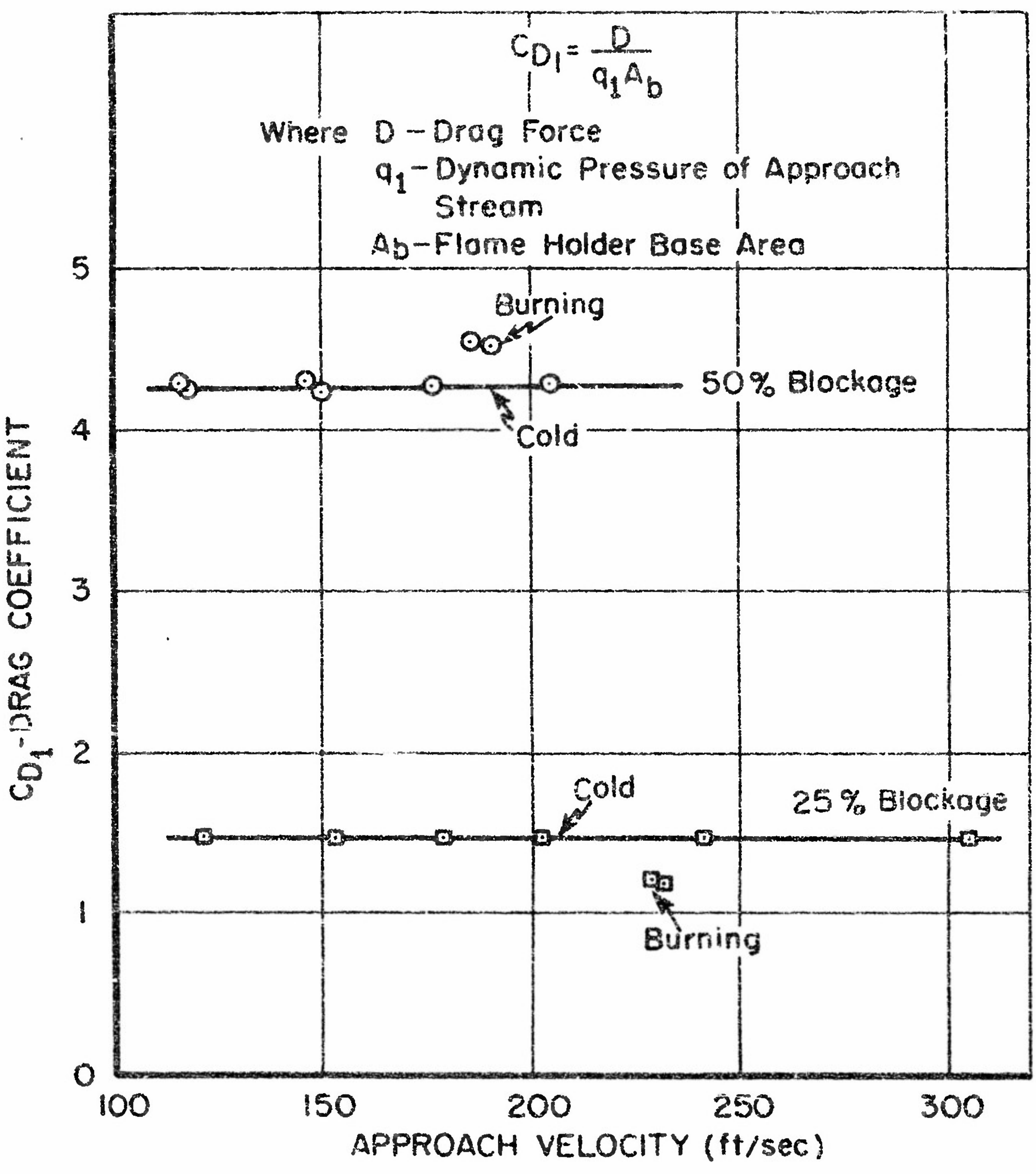


Fig. 10.5-2 EFFECT OF APPROACH VELOCITY ON THE DRAG COEFFICIENT FOR VARIOUS FLAME-HOLDER BLOCKAGES

figure for definition) with velocity is noted for either the 25 or 50 per cent blockage configuration over the velocity range tested. This represents an approach Mach number range from 0.05 to 0.22. Other investigators [25,26] are in agreement with this observation when the operation is in the incompressible region.

The difference between burning and cold flow drag coefficients is small (see Fig. 10.5-2). It was found for the 25 per cent blockage baffle that the burning drag coefficient was slightly lower than the cold, and for the 50 per cent blockage baffle that the burning drag coefficient was slightly higher than cold. Results reported in [26] showed that for conical baffles, the burning and cold drag were nearly the same.

The drag coefficient, as defined in Fig. 10.5-2, is based on the approach-stream dynamic pressure. The value of this coefficient is dependent on the blockage of the baffle. The table below shows values of drag coefficient, C_{D_2}, which give a value more independent of blockage. This drag coefficient is based on the dynamic pressure of the stream in the plane of highest blockage past the baffle. A fair correlation is obtained and by using a mean value of these drag coefficients, one could predict the drag of various blockage baffles.

Baffle	Flow Condition	$C_{D_2} = \frac{D}{A_b q_2}$
25 per cent	Cold	0.82
25 per cent	Burning	0.70
50 per cent	Cold	1.03
50 per cent	Burning	1.12

where

D = drag force,

q_2 = dynamic pressure in plane of highest blockage past baffle, and

A_b = baffle base area.

Probably by using the dynamic pressure in the vena-contracta formed by the baffle, a better correlation could have been obtained. An analysis which assumes sudden enlargement of flow area is given in [25]. This method introduces an area-contraction coefficient to give empirical values of drag.

Figure 10.5-3 is a collection of drag data [25,26,5] to show the effect of blockage on the drag coefficient (based on full duct area) for various single-plane baffles. The baffles vary from simple V-gutters and cones to complicated grid arrangements. The drag coefficient appears to be primarily a function of blockage with possible secondary effects due to baffle geometry.

Staggered Baffles

One method of reducing the drag of high blockage baffles is by staggering the elements.

Data from the Esso Laboratories [5] showing the effect of axial spacing between baffles on over-all drag coefficient (C_D) are given in Fig. 10.5-4. The baffles tested were two V-gutters each having a blockage of 25 per cent. No change in drag coefficient was noted for a change of approach Mach number from 0.05 to 0.22. It can be seen that by staggering the baffles approximately one width that the drag coefficient is decreased about 45 per cent. Further spacing helps to decrease the drag coefficient, but this decrease with spacing becomes less noticeable. The over-all drag coefficient approaches a value of twice the coefficient of a single 25 per cent blockage gutter as the spacing between the gutters becomes large. These data indicate that staggering of baffles in a baffle-type combustor will allow considerable reduction in the drag for high blockage engines.

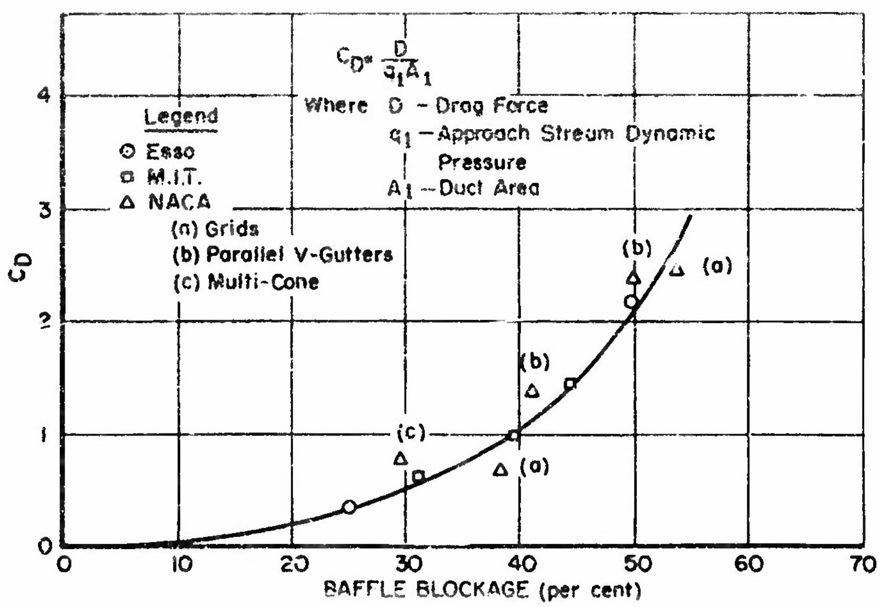


Fig. 10.5-3 EFFECT OF BAFFLE BLOCKAGE ON DRAG COEFFICIENT (APPROACH MACH NO. = 0.16)

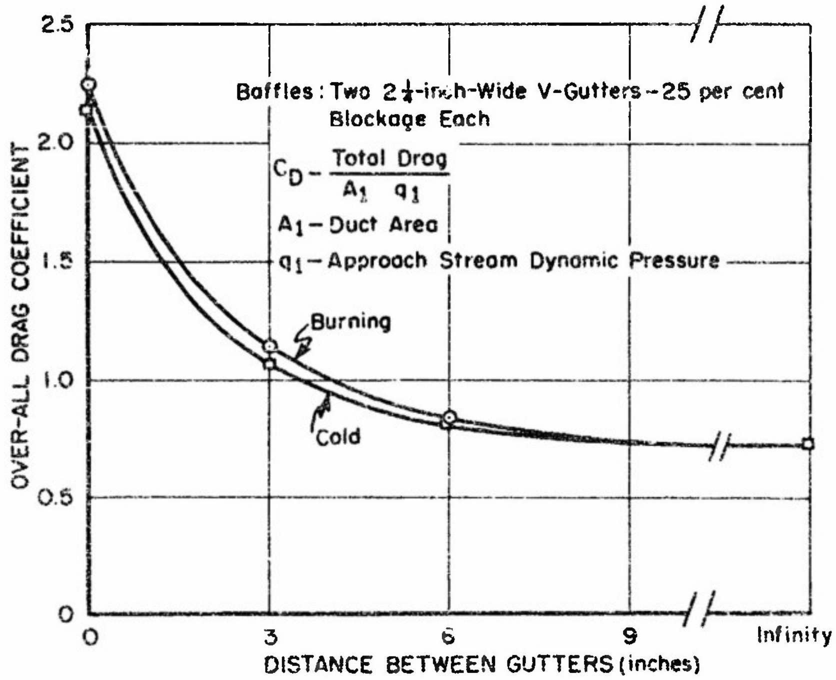


Fig. 10.5-4 EFFECT OF SPACING BETWEEN BAFFLES ON THE OVER-ALL DRAG COEFFICIENT

Drag Data Applied to Complete Engine

The preceding data may be applied to predict over-all drag coefficients of baffle-type ramjet engines. Since it was shown in Fig. 10.5-3 that the drag coefficient is primarily a function of blockage, the shape of the baffles may be neglected and only the blockage considered. For a single-plane combustor without an innerbody being in the same plane as the baffles, Fig. 10.5-3 may be used directly. In many ramjet-engine designs, the innerbody is carried back to the combustion chamber and is cut off to form part of the baffle arrangement. The over-all drag coefficient of an arrangement of this type can be estimated by considering the drag of each element. Referring to the value of the drag coefficient (C_{D_2}) which was shown to be fairly constant with blockage, one can calculate the over-all coefficient of an innerbody-baffle engine in the following manner. If the innerbody is considered infinitely long on the upstream side, only base drag is then considered. The frictional drag on the surface of the innerbody and the form drag at the missile inlet are not charged to the combustor. Unpublished data from the Esso Laboratories indicate that the base drag accounts for approximately half the total drag force on a baffle, or

Regular Baffle $\quad C_{D_2} \approx 0.9$

Innerbody $\quad C_{D_2} \approx 0.45$

For a complete combustor made up of an innerbody flame holder plus baffles the over-all drag coefficient, C_D, is

$$C_D = 0.9 \frac{A_b q_2}{A_1 q_1} + 0.45 \frac{A_{IB} q_2}{A_1 q_1}$$

where

A_b = area of baffle,

A_{IB} = area of innerbody,

A_1 = combustion-chamber full area,

q_2 = dynamic pressure in plane of highest blockage past baffles and innerbody, and

q_1 = dynamic pressure based on full combustion-chamber area.

Staggering baffles makes the drag prediction more complicated. The results shown in Fig. 10.5-4 are for a 50 per cent blockage configuration and the effect of spacing referred to in baffle widths for other blockages is not known. If one replots the abscissa in terms of baffle width and assumes this correct and further assumes that the percentage reduction in drag coefficient with spacing is the same for all blockages, then a prediction of drag coefficient for staggered baffles can be made provided the elements have nearly the same blockage. This is shown in Fig. 10.5-5.

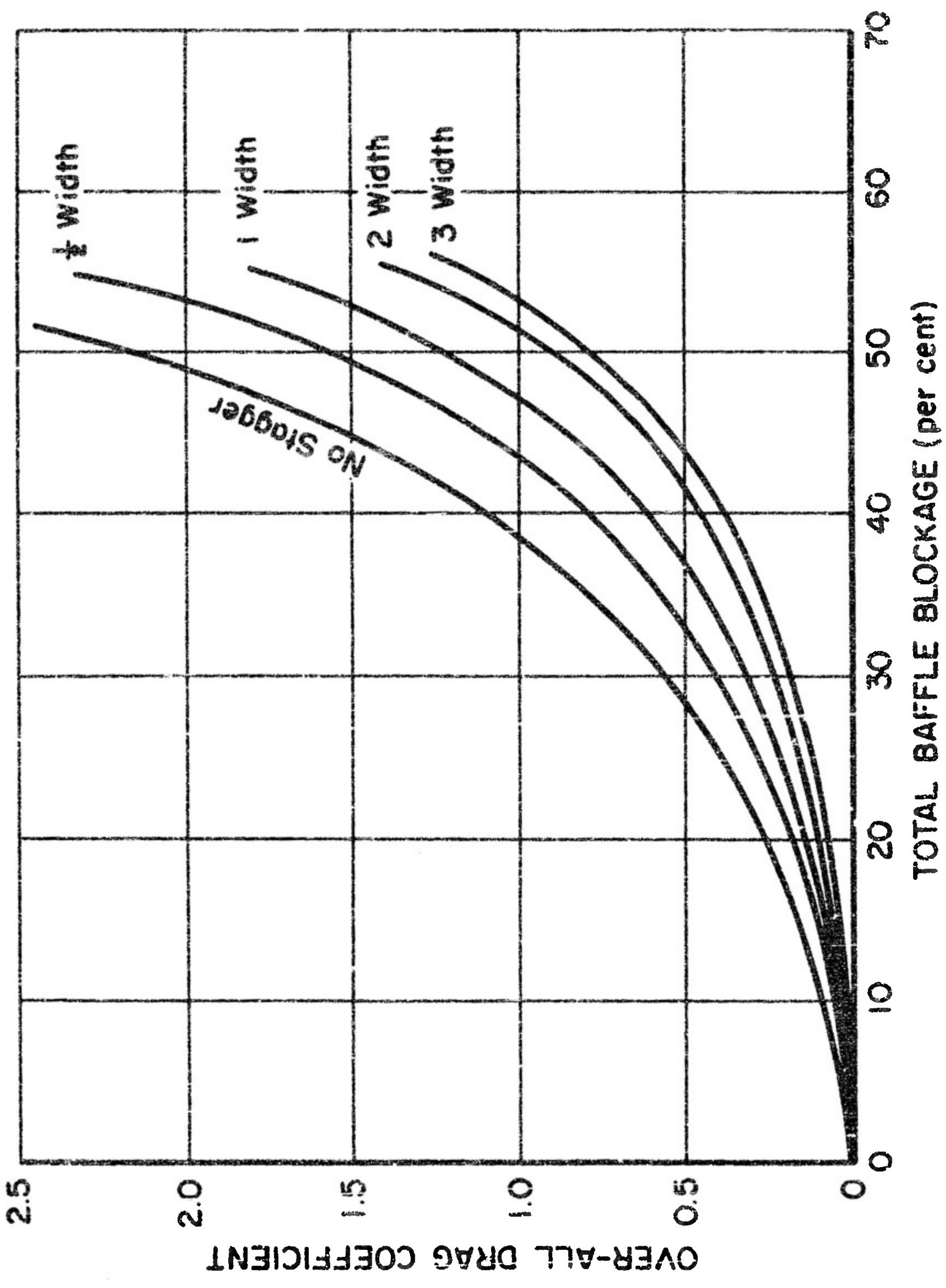


Fig. 10.5-5 PREDICTED EFFECT OF STAGGERED BAFFLES ON OVER-ALL DRAG COEFFICIENT

10.6 IGNITION

Prompt ignition of the combustor's air-fuel mixture is another essential requirement of engine design. Ideally, the combustor should instantaneously deliver a specified thrust at the end of the boost period. However, in the launching of the missile, there may be delays other than that associated with separation of the booster rocket. These include filling the fuel lines with fuel, filling the combustion chamber with a combustible mixture, and then actual ignition of the combustible mixture. There is also an additional time delay to burn off and expel starting constrictors when they are used to help initiate combustion. Only the variables which affect the actual ignition will be considered in this section. It will be shown that the methods and characteristics of starting a test-stand engine may be entirely different from those found in a flight unit.

General Considerations

The minimum ignition energy (optimum composition, homogeneous, quiescent mixture) of typical hydrocarbon fuels used in ramjet engines is of the order of 0.00025 joule at one atmosphere pressure. At lower pressures (1/10-atmosphere) this energy requirement may increase 125 times. It has been shown [34,35] in a flow system of propane and air that the ignition energy increases with increased velocity, turbulence, and reduced pressure. Also in the same system, the energy is a minimum for mixtures slightly richer than stoichiometric. Investigations [36] on a turbojet combustor indicate that the ignition energy requirement decreases with increased fuel

volatility. When considering an electric spark source [37], certain electrode parameters such as spark gap, electrode size, electrode material, and spark duration also affect the energy requirement.

Since it was shown above that velocity affects the ignition energy, the "ignition source" in baffle engines is located in the sheltered region of one of the flame holders or in some special holder for this purpose. The location of this igniter should be such that, once the combustible mixture in its wake ignites, the flame will propagate to the surrounding baffles. Examples of the location of the ignition sources can best be seen in the Survey of Baffle-Type Combustors (Appendix I). Spark ignition is used almost exclusively on test-stand engines because continuous re-use of this source is possible. The flare is a one-shot affair and is used in ground testing only when simulated missile starting tests are made. In the past, engines have been ignited in flight by flares but more recently spark-ignition systems have been used. One developed for the Talos flight combustor [27] has proven very satisfactory. This flight-spark-ignition system produces 0.05 joule per spark at 120 cycles or approximately 200 times the minimum determined under idealized conditions for one atmosphere pressure. If the missile is of small size, over-all weight limitations may dictate the use of flares. On the other hand, if the combustor is to be turned off during its trajectory and re-ignited, then spark ignition is dictated. Flares have been less reliable than electric sparks in that there is a certain percentage of duds and the wiring system is easily damaged. The characteristics of flares such as burning time, powder type, and structure will not be discussed in this section. Other factors which affect the ignition delay are fuel type, air-fuel ratio, and starting sequence. This latter item refers to the time when fuel is first injected in reference to the time when the ignition source is turned on.

Ground testing in altitude chambers* offers starting difficulties due to the increase in the ignition-energy requirement at low pressures. This has been overcome by the addition of small amounts of hydrogen in the region of the spark igniter. The minimum ignition energy of hydrogen is about 1/10 that of the normal hydrocarbon-type fuels.

The combustor once ignited will have a certain air-fuel range over which stable combustion occurs. Within these stability limits, there is a narrower range in which smooth ignition can be obtained. An example of this is shown in Fig. 10.6-1 for a 6-inch engine [8] where the spark-ignition range is only slightly inside the smooth-burning range. Replacing the spark with a flare did not change this relationship. If a nonhomogeneous air-fuel distribution exists, the smooth spark-ignition range will change for different locations of the ignition source.

Cold Flow

The flow state in the area surrounding the baffle elements prior to combustion has an appreciable effect on the ignition delay and the engine may not, under certain conditions, start at all. The missile Mach number and altitude at the end of boost,

*To simulate altitude conditions, the ramjet may exhaust into a chamber in which the pressure is reduced by use of ejectors or for intermediate altitude simulation, this may be achieved by equipping the ramjet with an exit diffuser which is open to the atmosphere. This latter method is described in [43] and has been successfully applied in a number of starting tests.

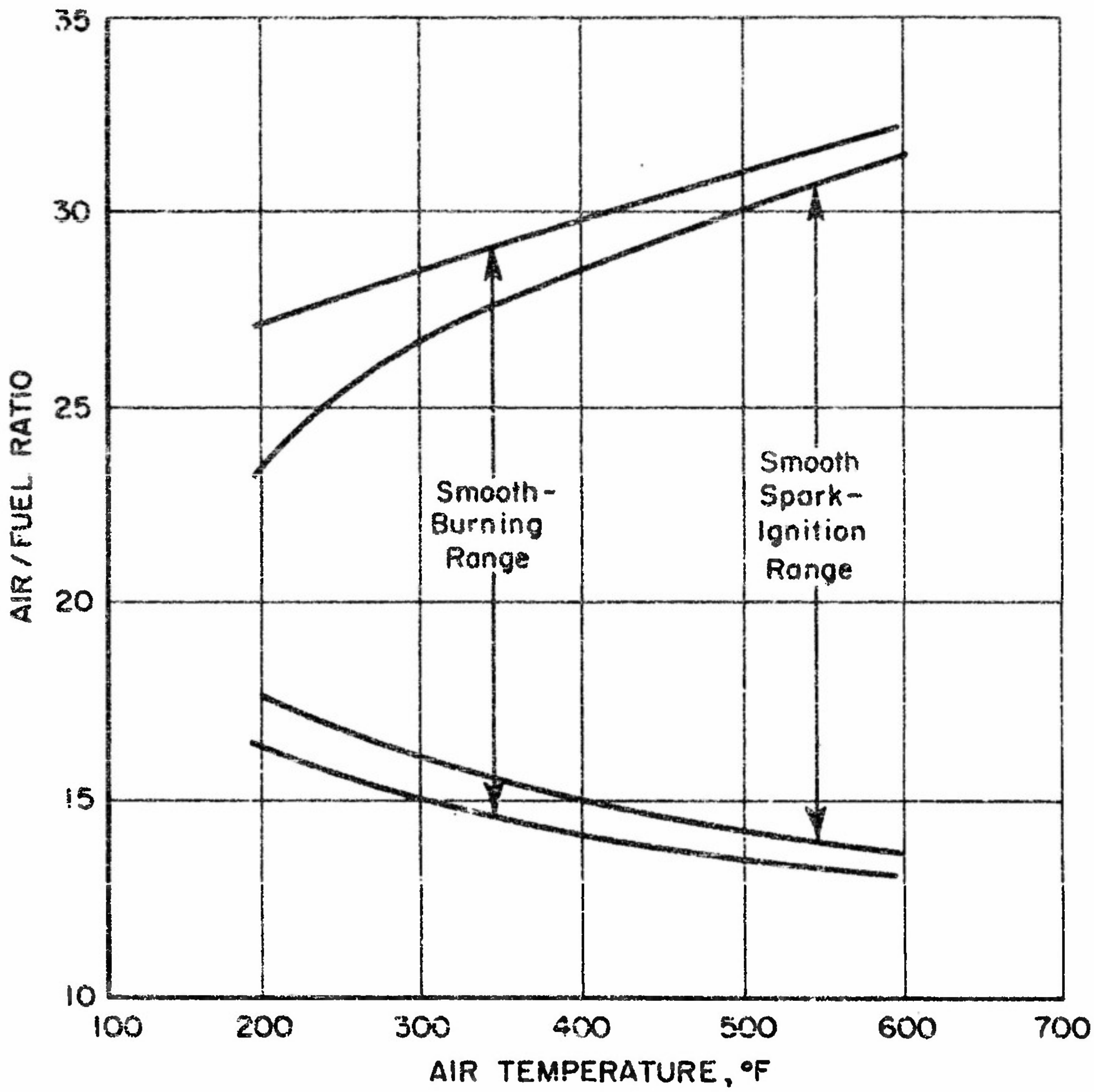


Fig. 10.6-1 RANGE OF SMOOTH BURNING AND SPARK IGNITION AS A FUNCTION OF INLET AIR TEMPERATURE

along with missile geometry and diffuser characteristics, fix the combustion chamber cold flow entrance conditions. An added factor [28] not found in free-jet ground starting tests is the aspirating action in flight of the supersonic external air flow past the tailpipe which produces an even lower ramjet exit pressure. With the above conditions and the high blockages used in normal baffle-type combustors, choking may occur at the flame holders provided the exit nozzle area is not less than the flow area past the baffles. Downstream from this sonic surface, the flow is supersonic and expanding until it passes through shock waves which raise the pressure to match exit conditions. This shock configuration about a baffle [40] is shown in the spark shadowgraphs in Figs. 10.6-2 and 10.6-3. If the shock occurs close to the flame holder, the flow will be subsonic and the pressure relatively high in a partion of the region immediately behind the flame holder, making starting comparatively easy; on the other hand, if the shock wave is located some distance downstream from the flame holder, flow is supersonic and pressure is low throughout the region where burning must start, making ignition difficult. Ignition of a baffle combustor under this latter condition usually produces a residual flame which extends a short distance downstream from the flame holder but does not propagate through the surrounding combustible mixture. Apparently there is overmixing in going through the shock wave which quenches the flame. It was found [41] that if the heat release from the baffle was steadily increased by the addition of hydrogen, then the shocks approached nearer and nearer to plane shocks and moved upstream. A condition was finally reached where the shock moved to the throat of the baffle and the stream became everywhere subsonic.

One method used to insure a subsonic regime about a flame holder was the use of two sets of flame holders, one upstream of the other, as exemplified in 6-inch ramjet testing [8] and in the

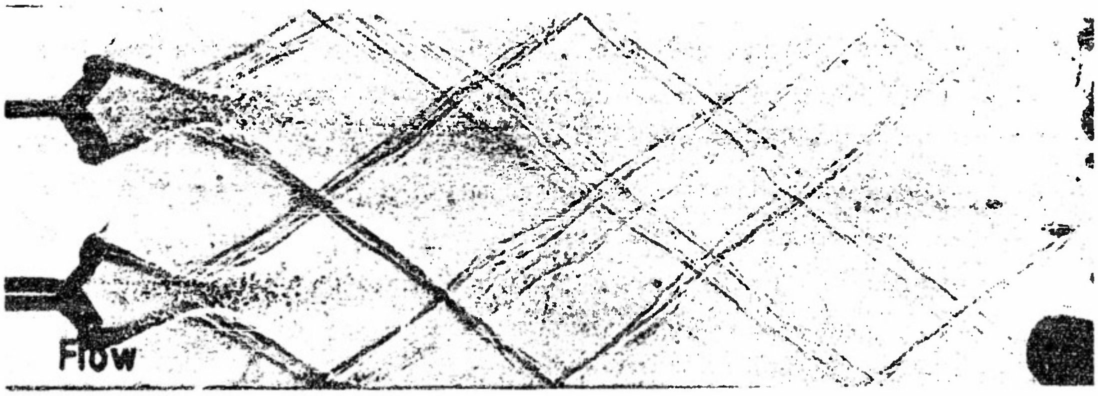


Fig. 10.6-2 SPARK SHADOWGRAPH OF SUPERSONIC FLOW ABOUT TWO GUTTERS IN A DUCT (STAGNATION PRESSURE 20 LB/IN^2 GAUGE)

Fig. 10.6-3 SPARK SHADOWGRAPH OF SUPERSONIC FLOW ABOUT TWO GUTTERS IN A DUCT (STAGNATION PRESSURE 15 LB/IN^2 GAUGE)

two-stage, vortex-piloted BTV [24]. With such units, choking occurs at the downstream set of flame holders so that flow is subsonic past the upstream set where ignition first takes place. This same idea can be applied to single-stage baffle combustors to improve starting ability. Rather than modify the geometry of a combustor of this type, which gives satisfactory performance while burning, a temporary constrictor can be placed downstream from the main flame holder to produce subsonic flow at the main flame holder. For example, the XPM had a 55 per cent blockage constrictor mounted 11 inches downstream from the flame holders. These added constrictors can be of almost any shape and can be connected to the main flame holder by fusible rods or straps. After starting is accomplished, the rods burn off and the constrictors are blown out the rear of the ramjet. Using these constrictors, and with an exit diffuser on the unit, starting has been found to be practically instantaneous and completely reliable [28]. There is some loss in thrust during the interval before the rods burn off, but this can be controlled by having the rod material designed so that prompt burn-off occurs.

Further studies [29] of problems associated with initiating combustion in baffle-type ramjets show that it is possible to design a baffle with high blockage area that would permit satisfactory starting when a supersonic field existed in its wake. This was done with a correctly designed secondary flame holding system inside a cylindrical shield. The secondary flame holders transmitted enough heat energy to the cold air-fuel mixture flowing past the baffle so that full combustion was established.

10.7 BURNOUT

Burnout of flame holder parts has been a major development problem in baffle-type ramjets. This occurrence of metal burnout is usually encountered with high mass flow and pressure conditions found during sea-level operations. The causes of burnout can be related to the pressure fluctuations within the combustion chamber. Actual burnout itself seems to be caused by flames on both sides of the baffle elements which may be a result of periodic flashback or a stabilized flame ahead of the baffles. During normal smooth operation, the baffle elements reach an equilibrium temperature in the order of 1300 degrees Fahrenheit or less. The strength of materials used in the fabrication of baffles should be adequate for this temperature range. Chapter 12 gives a more complete discussion of heat transfer to combustor elements.

Since burnout is a problem of obtaining smooth flow past the baffles, one should have an understanding of how to eliminate instabilities which lead to ignition of the combustible mixture upstream of the baffles or to periodic flow reversal. There is very little quantitative understanding of the flow and pressure oscillations occurring in ramjets. Several authors [30, 44] have shown that the frequency of oscillation can be related to resonant frequencies of the system and some indications of where one might expect an instability have been determined. As yet, however, it is not possible to predict the magnitude of oscillations of the various types, so the ramjet designer is forced to follow a few crude rules; elimination of undesirable oscillations that may arise are left to the test program. From the development engineer's viewpoint the flow fluctuations which may cause burnout can be classified into the following groups.

1. Flashback in boundary layer.
2. Coupling between fuel flow and combustor pressure oscillations.
3. Periodic flow fluctuations in the wake of flame holders.
4. Poor combustion chamber entrance flow conditions.

These pressure fluctuations will be discussed according to the above groups and means of overcoming these instabilities will be suggested.

A discussion of flashback in the boundary is given in Reference [30]. It was found, for the combustor used, that when operating near an equivalence ratio of 1.0 with a homogeneous air-fuel mixture, flame upstream of the baffle resulted from a detonation of the gas mixture which begins at the intersection of the flame front and the duct wall. The detonating flame then traveled upstream through the wall boundary layer and finally ignited the whole mixture between the fuel injector and baffle. Rough burning could be completely eliminated by injecting water along the wall boundary layer. Since flashback was caused by detonation of the vaporized rich mixtures along the wall boundary layer, unvaporized fuel or lean air-fuel mixtures at the wall also prevent this type of rough operation. This has been demonstrated by 6-inch combustor [8] tests at the Esso Laboratories (see the section on fuel type and vaporization) where the unit became rough just before rich blowout. The rich limit was shifted to richer values of over-all air-fuel ratios by decreasing the amount of fuel along the combustor wall or using partially vaporized fuel. Excessive tailpipe heating is also prevented with a fuel distribution that gives lean mixtures at the wall. Experience at the Esso Laboratories (unpublished) in developing test apparatus for flame spreading studies indicates that a thin wall boundary layer will also prevent this type of periodic flashback. The pressure fluctuations accompanying the

appearance of flames upstream of the baffle had rather large amplitudes and frequencies of about 35 to 60 cycles per second. Contributing factors other than those given above (rich homogeneous air-fuel mixtures and boundary layer thickness) influence rough burning. It has been noted that combustors capable of high efficiency with relatively short tailpipes are much less susceptible to this type of rough burning. Usually a centrally located baffle is prone to rough burning because of the large distance required before the flame intersects the combustion-chamber wall. However, the flame can be made to intersect the wall at short distances from the flame spreaders by using a number of small baffles equally spaced across the combustor chamber. This type of combustor usually gives smoother operation. In the same connection, increasing the heat output from piloted burners has a tendency to decrease rough burning, because higher efficiencies are usually obtained in a shorter distance. This occurs if the pilot heat output is sufficient to show an effect on efficiency.

Another type of pressure fluctuation that may be encountered is associated with a coupling between the fuel-injection system and the burner. This instability can cause structural damage because of the large magnitude of pressure pulses or trigger burnout as associated with aerodynamic flow discussed in one of the paragraphs to follow. The pressure cycle proceeds in the following manner. Assume that an arbitrary pressure pulse arising from some cause reaches the fuel injector and causes a slight temporary decrease in fuel flow. When the portion of lean mixture reaches the combustion chamber the pressure level drops. The resulting negative pulse then travels upstream causing an increase in fuel flow. The resulting rich mixture brings about an increase in burner pressure when it reaches the flame holder and the cycle repeats. It was found in both liquid rockets [44] and ramjets [30] that a fuel-injection system which

requires a high pressure to supply sufficient fuel invariably resulted in smoother operation. For rocket operation, it appeared that this type of instability is not possible if the injector-pressure drop exceeds one half the mean chamber pressure.

Still another instability which may lead to burnout will be described here. A periodic, high frequency pressure and flame oscillation was encountered in a United Aircraft Corporation [22] innerbody engine shown in Fig. 10.7-1(b) but never in an outerbody type [Fig. 10.7-1(a)]. This instability was characterized by a sudden and substantial increase in combustion efficiency (Fig. 10.7-2), and a very loud high pitched sound which was designated "screech". The predominant frequency measured during screech was of the order of 2500 to 3000 cycles per second. An investigation of this phenomenon was made and reported by the United Aircraft Corporation [23]. The conclusions of this study are as follows:

1. Screech in the United Aircraft Corporation ramjet engine is an aerodynamic-combustion phenomenon in which a vortex forms periodically at the flame spreader. This process is accompanied by pressure pulsations at a reproducible frequency, a high order of mixing, and nearly complete combustion.
2. Screech in the United Aircraft Corporation ramjet engine is not a simple acoustic resonance in the combustion chamber.
3. Increasing the flame speed of the inlet mixture increases both the frequency of screech and fuel-air ratio range over which it occurs.
4. Geometry changes in the region of the flame spreader strongly affect the screech process, but variations in length and diameter of combustion chamber and acoustic properties of the upstream piping have little effect.

From spark-schlieren photographs taken and arranged according to sequence, it was possible to follow the details of flame movement during a screech cycle. The outstanding feature of the

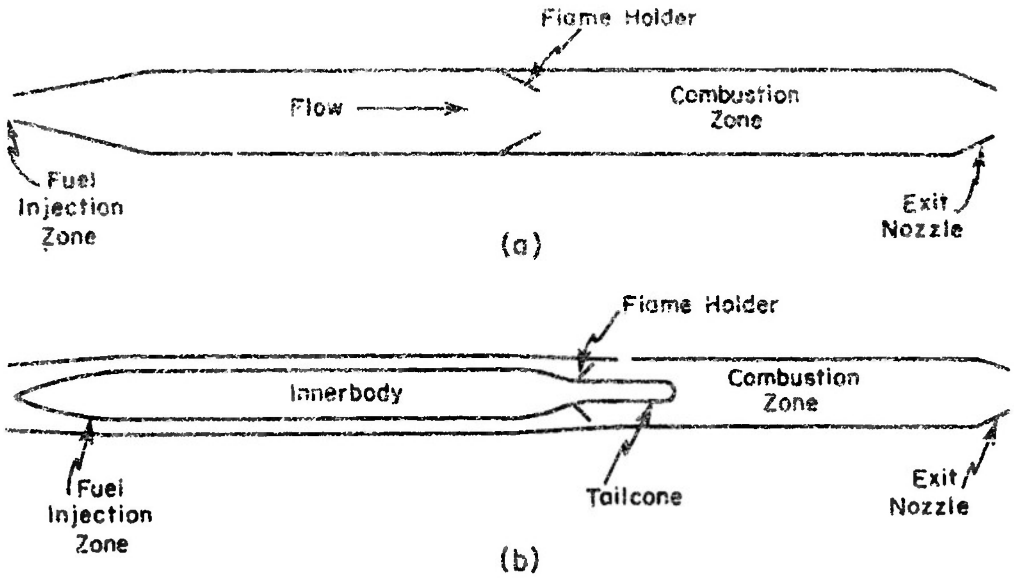


Fig. 10.7-1 UNITED AIRCRAFT OUTERBODY- AND INNERBODY-TYPE RAMJET ENGINES

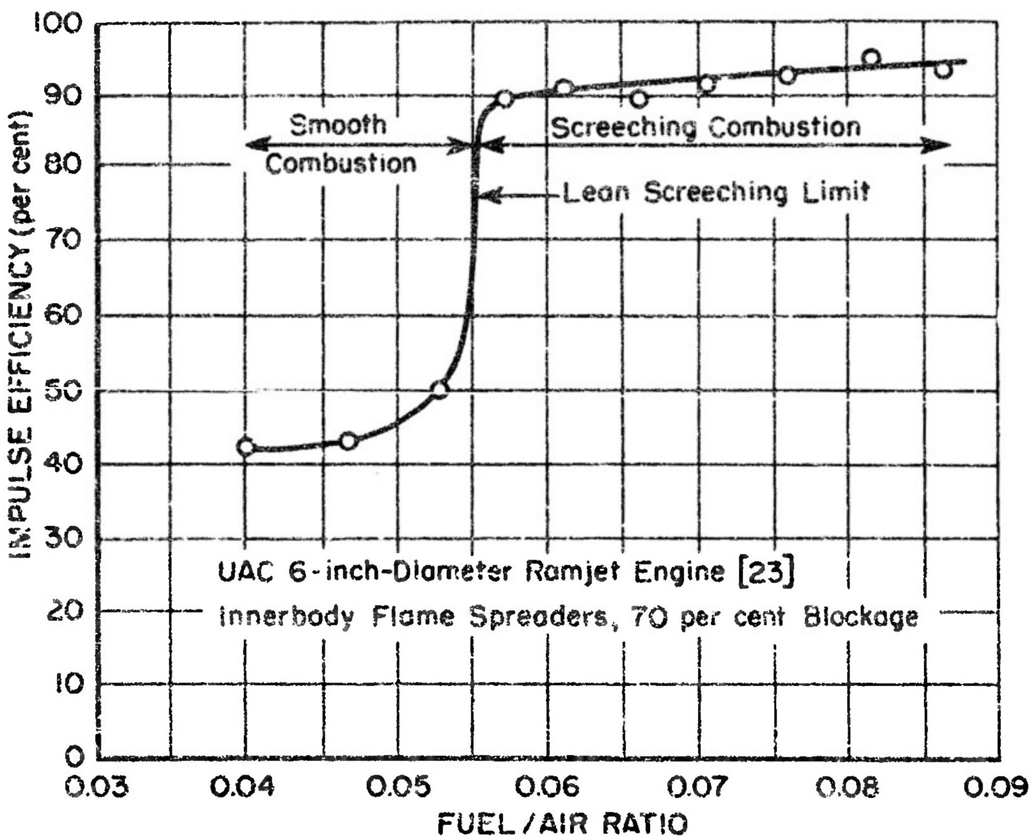


Fig. 10.7-2 EFFECT OF SCREECH ON IMPULSE EFFICIENCY

flame movement is the origin of a vortex at the flame spreader and its growth as it moves downstream and out toward the combustion-chamber wall. At the time that one has apparently developed fully and before the next vortex has started, the flame is seen to fill the entire combustion chamber. It is apparent that a high order of mixing of fuel-air charge with hot products of combustion occurs during the cycle. Although high efficiencies are observed in a "screeching" burner, there may be serious burnout problems accompanying this phenomenon. The sequence spark-schlieren photographs during any screech cycle show that for the United Aircraft Corporation combustor, the flame actually travels upstream a short distance along the front surface of the flame holder. This did not present any burnout problem for this configuration, but under the proper circumstances, it could be troublesome.

The air flow at the entrance of the combustion chamber along with the aerodynamic flow around the fuel injector, struts, fastenings, and miscellaneous hardware upstream of the flame holder may also under certain conditions cause burnout. With a poor subsonic-diffuser design it is possible that separation along the diffuser or innerbody wall may result in thick boundary layers. If a combustible mixture is present in this layer, flow pulsation may cause ignition of the gases in this section. Similarly, the flow around the fuel injector and other parts between the fuel and baffle should be aerodynamically clean, since it has been found in a number of cases that burnout was caused by a flame which traveled upstream and held in the wake of some poorly streamlined component.

APPENDIX I

SURVEY OF BAFFLE-TYPE ENGINES

MARQUARDT 28-INCH ENGINE
Refs. [1,2,3], 1950

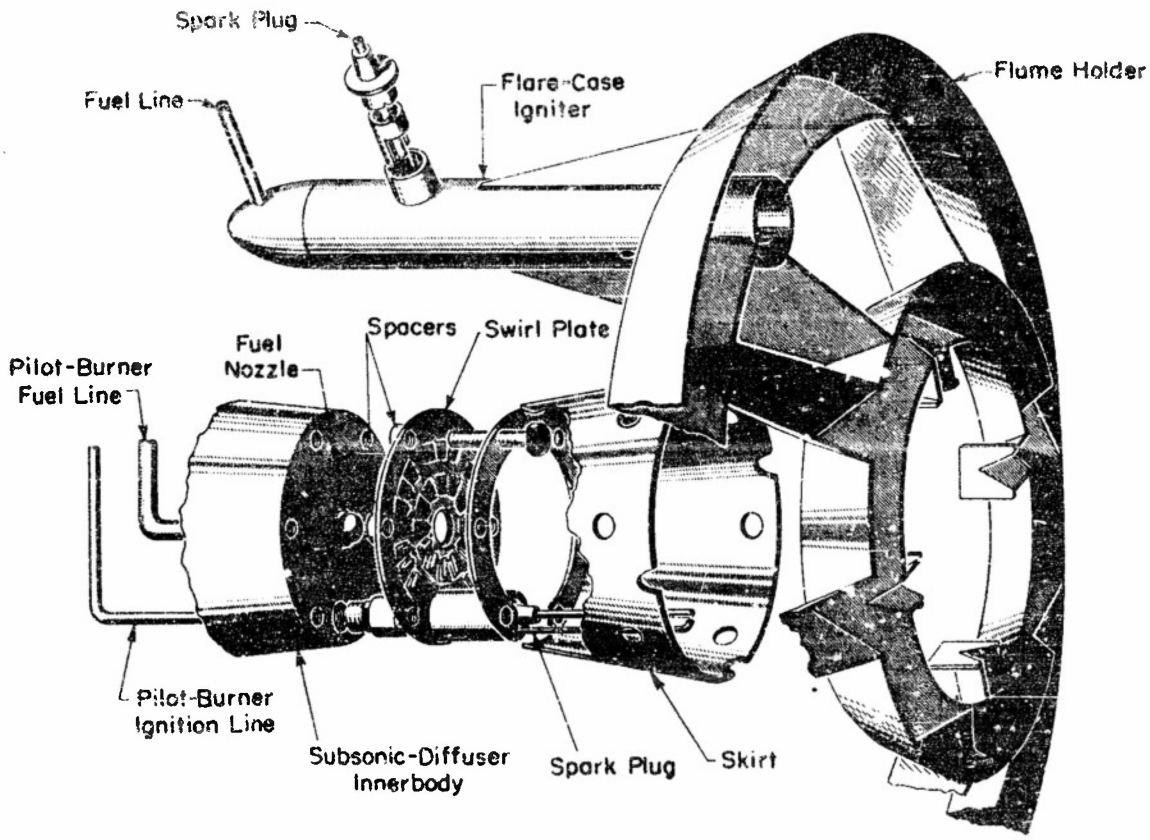


Fig. 10A-1 EXPLODED VIEW OF PILOT-BURNER AND FLAME-HOLDER ASSEMBLY

I. Expected Missile Performance

(To specifications of Grumman XSSM-N-6)

II. Type Combustor

A. Pilot - A can-type pilot is mounted on the blunt end of the diffuser innerbody. The pilot is made of a swirl plate six inches in diameter, mounted on 1/2-inch spacers. Attached to the swirl plate is a tapered skirt, 4.4 inches long and 7.8 inches in diameter at the downstream end. The pilot provides 7.7 per cent blocked area.

B. Spreaders - The flame spreaders consist of two, 2-inch wide, V-gutter annular rings on 11.8-inch and 22.8-inch diameters. The downstream end of the larger ring and the upstream end of the smaller ring are in the same plane as the pilot exit. Eight radial gutters connect the two annular rings while four radial gutters connect the pilot to the inner ring. The flame holders have a projected blockage of 45 per cent of the combustion-chamber area.

III. Ignition

A. Ground - Spark plug inside pilot

B. Flight - Flares in three cases located around the outer annular-flame holder (see Fig. 10A-1)

IV. Combustion Chamber

A. Diameter - 28 inches

B. Length - 57 inches (plus exit nozzle)

C. Inlet Mach Number - 0.14 to 0.17 (depending on exit nozzle used)

D. Combustor Drag

E. Exit Nozzle - 55 and 65 per cent

V. Fuel-Injection System

A. Fuel Type - Heptane is used for pilot and main fuel.

B. Injection System - Fuel is injected approximately 37 inches upstream of the flame holders in each of the four quadrants through four double-manifold circular-arc segments. Ten spring-loaded nozzles are in each segment, discharging upstream. Pilot fuel is injected through a nozzle; fuel flow varies from 14.8 to 3.0 per cent, with greater flow at lean over-all operations.

VI. Engine Performance

See Fig. 10A-2.

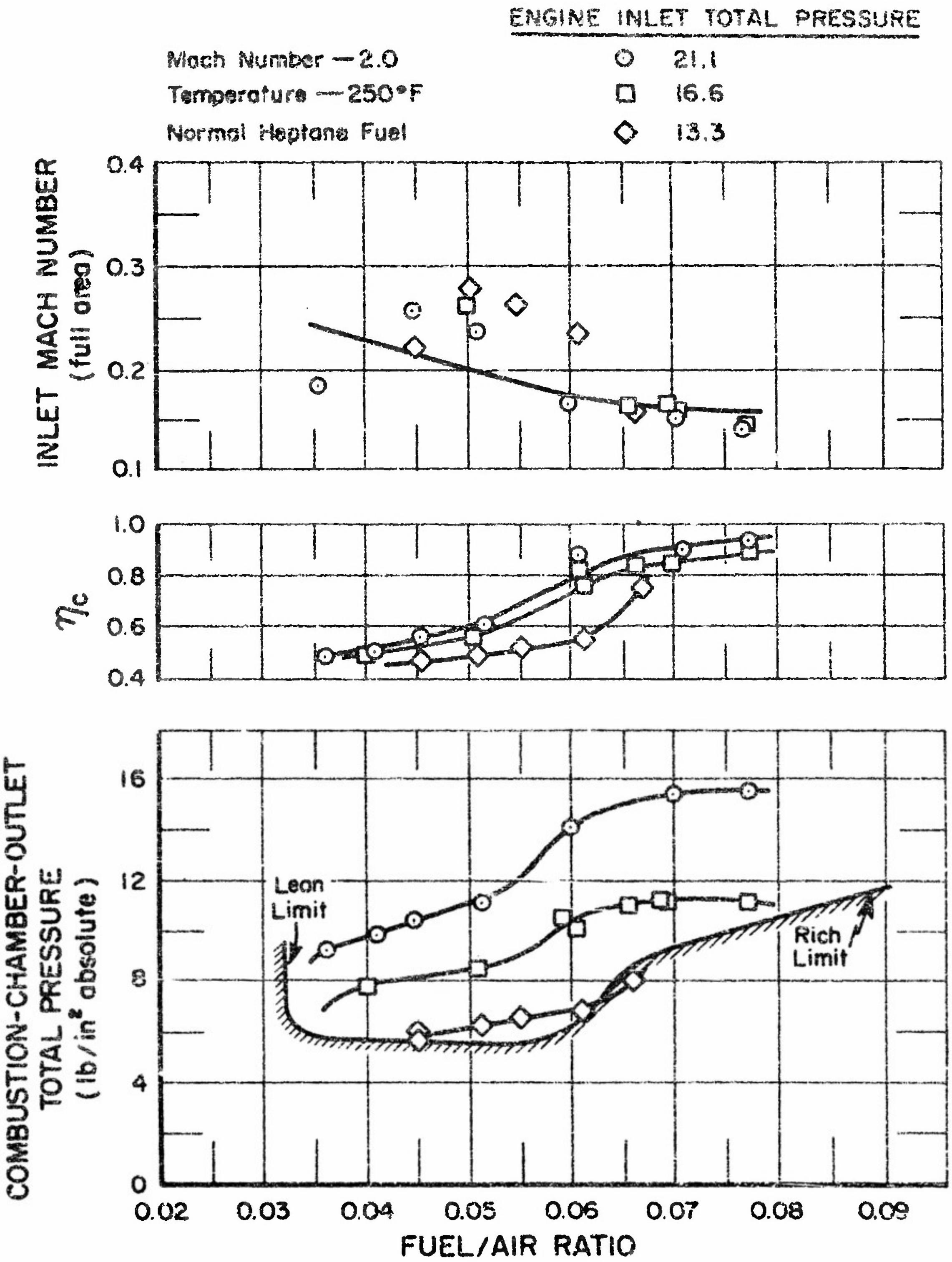


Fig. 10A-2 PERFORMANCE CHARACTERISTICS OF THE MARQUARDT 28-INCH ENGINE

MARQUARDT 20-INCH ENGINE

Refs. [47,48,49], 1949

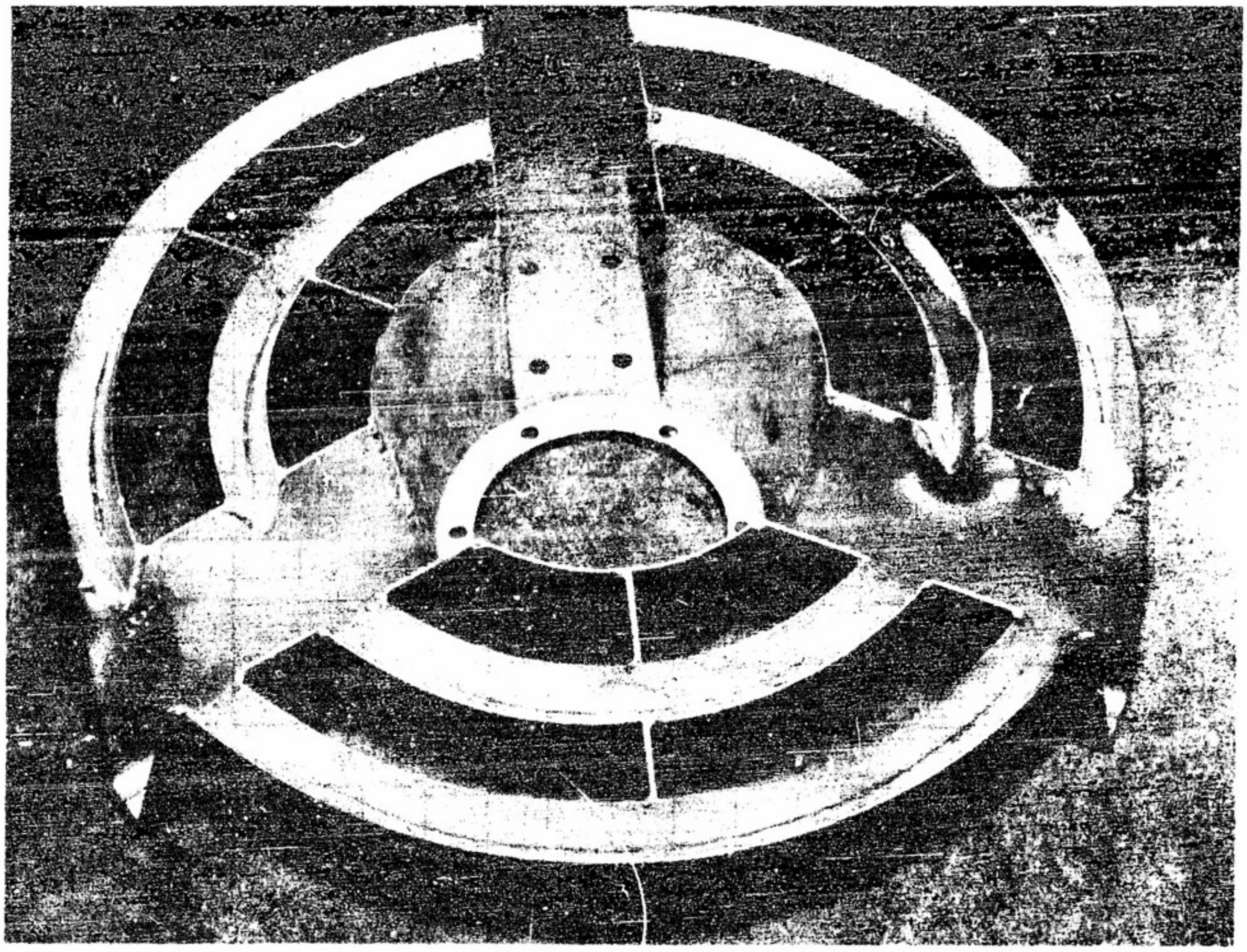


Fig. 10A-3 FLAME HOLDER USED IN MARQUARDT 20-INCH ENGINE

I. Expected Missile Performance

A. Mach Number - 2.35

B. Range - 10,000 yards

C. Maximum Altitude - 55,000 feet (initial) to 80,000 feet (maximum)

D. Launch Mach Number - 2.35

E. Engine-Design Air-Fuel Ratio - 22.2 (approximately)

II. Type Combustor

A. Pilot - A slightly conical pilot six inches in diameter is mounted on the downstream end of the innerbody.

There are no holes in the pilot skirt so that all the flow to the pilot must be recirculated from the downstream end.

B. Spreaders - Two sets of annular V-gutters, one inch wide, are used as flame spreaders and three, 3-inch-wide, open-box gutters connect the pilot and the spreaders. These box gutters fair into the blunt end of the central body-supporting longerons. The longerons split the annular-type entrance into three separate segments. There is approximately 53 per cent blockage by the flame-holding elements.

III. Ignition

A. Ground - Spark at upstream end of pilot

B. Flight - Flares at upstream end of pilot

IV. Combustion Chamber

A. Diameter - 20 inches

B. Length - 55.5 inches (plus exit nozzle)

C. Inlet Mach Number - 0.125 to 0.18 at diffuser exit (55 per cent exit nozzle)

D. Combustor Drag

E. Exit Nozzle - 55 to 75 per cent

V. Fuel-Injection System

A. Fuel Type - JP-3 is used for pilot and main fuel.

B. Injection System - The pilot has one spray nozzle mounted on its upstream end. In each of the three segments formed by the longerons in the diffuser are two circular-arc segment manifolds at different radii on which are mounted and pointed downstream a total of nine spring-loaded pintle fuel nozzles. The plane of the fuel injection is located approximately 15-1/2 inches upstream from the flame spreaders.

VI. Engine Performance

See Figs. 10A-4 and 10A-5.

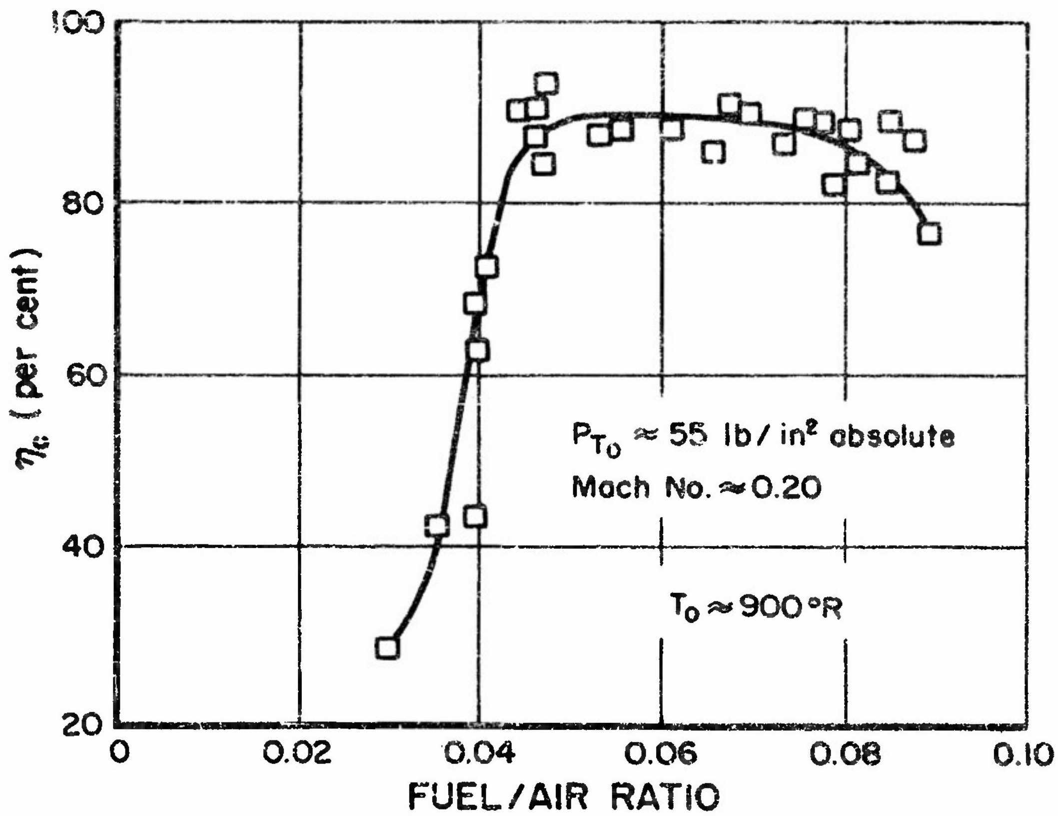


Fig. 10A-4 PERFORMANCE CHARACTERISTICS OF MARQUARDT 20-INCH ENGINE

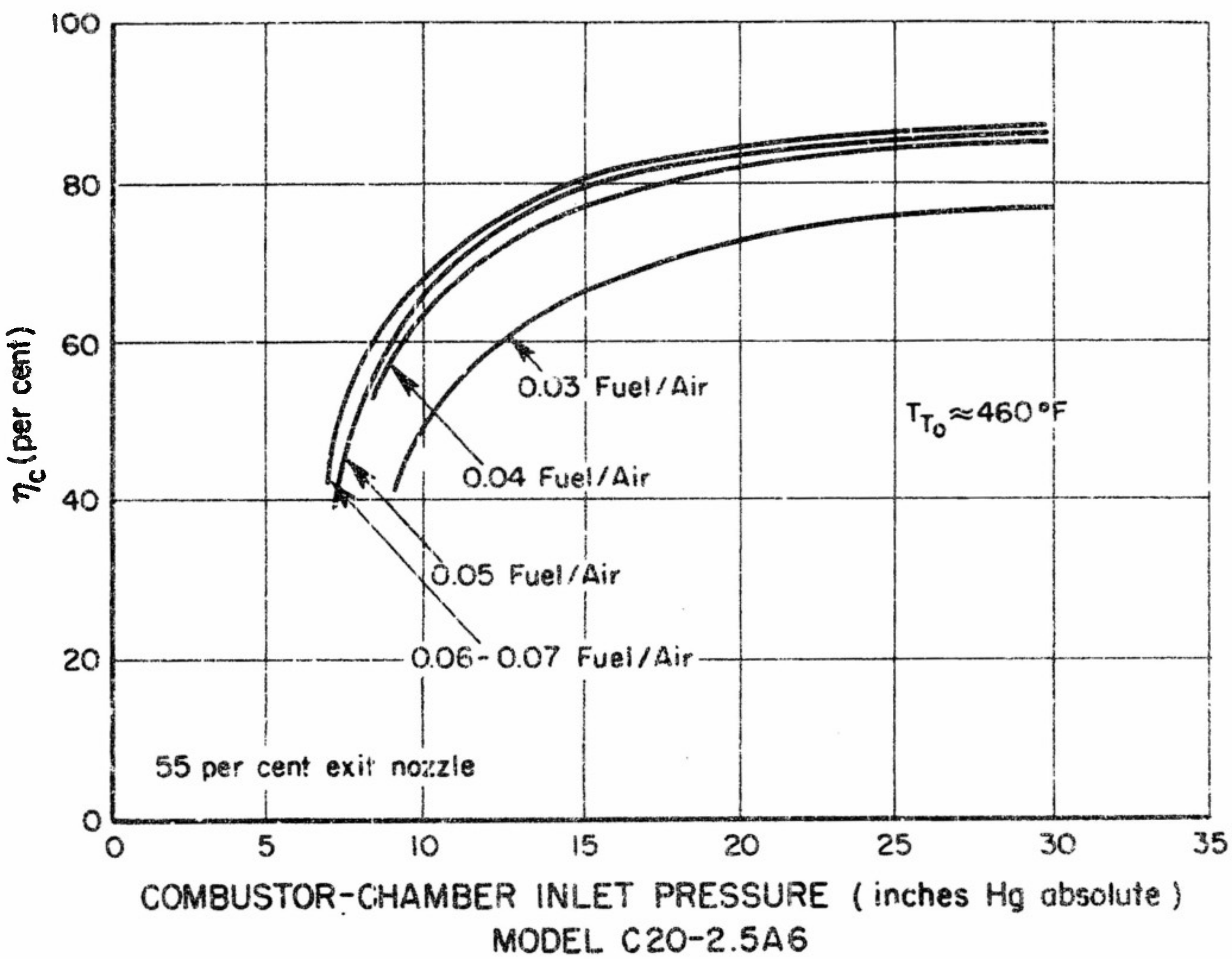


Fig. 10A-5 EFFICIENCY VERSUS INLET PRESSURE FOR VARIOUS FUEL-AIR RATIOS OF THE MARQUARDT 20-INCH ENGINE

NACA 20-INCH ENGINE

Ref. [40], 1953

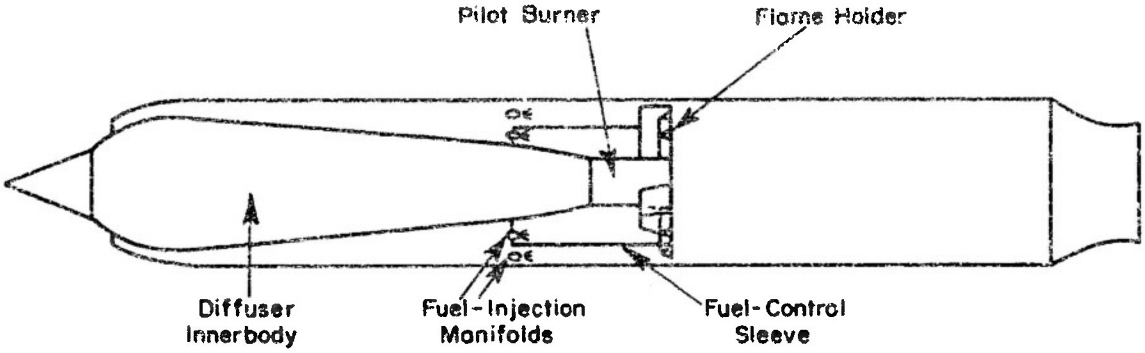


Fig. 10A-6 DIAGRAM OF NACA 20-INCH ENGINE

I. Expected Missile Performance

No application

II. Type Combustor

A. Pilot - The ramjet is a center-body type and the blunt end of the center body forms the pilot. The pilot burner is six inches in diameter and eight inches long. Louvers near the upstream end of the pilot burner provide air for pilot combustion.

B. Spreaders - Three gutters, which are three inches wide at the open end, extend radially from the downstream end of the pilot burner. These gutters form channels 4.4 inches deep and are mounted on the blunt ends of the innerbody support. Two circular V-gutters one inch wide interconnect the radial gutters at radii of 6.0 and 8.5 inches. Total blockage of flame holder is 55 per cent of combustion-chamber area.

III. Ignition

Ground - Ignition of the pilot burner is accomplished by means of an igniter which extends radially into the pilot burner and burns an electrically-ignited mixture of propane and air.

IV. Combustion Chamber

A. Diameter - 20 inches

B. Length - 48 inches

C. Inlet Mach Number - 0.18 at a fuel-air ratio of 0.065

D. Combustor Drag

E. Exit Nozzle - 55 per cent

V. Fuel-Injection System

A. Fuel Type - JP-4

B. Injection System - The engine fuel is injected through 27 nozzles which are located 17 inches upstream of the flame holder. The spray is in a downstream direction. The nozzles are located in two concentric circular manifolds, each of which is divided into three segments because of the innerbody supports. Each outer manifold segment is equipped with five equally-spaced fuel nozzles and each inner segment has four equally-spaced nozzles. A single fuel nozzle supplies fuel to the pilot burner. A cylindrical control sleeve has been installed which extends from between the fuel-injection manifolds downstream to the plane of the annular flame-holding gutters. The control sleeve is designed to capture approximately 40 per cent of the engine air flow and to confine all the fuel injected by the inner manifold within the control sleeve, thus making it possible to maintain a rich local fuel-air mixture at the flame holder while the engine is operating at a lean over-all fuel-air ratio.

VI. Engine Performance

See Fig. 10A-7.

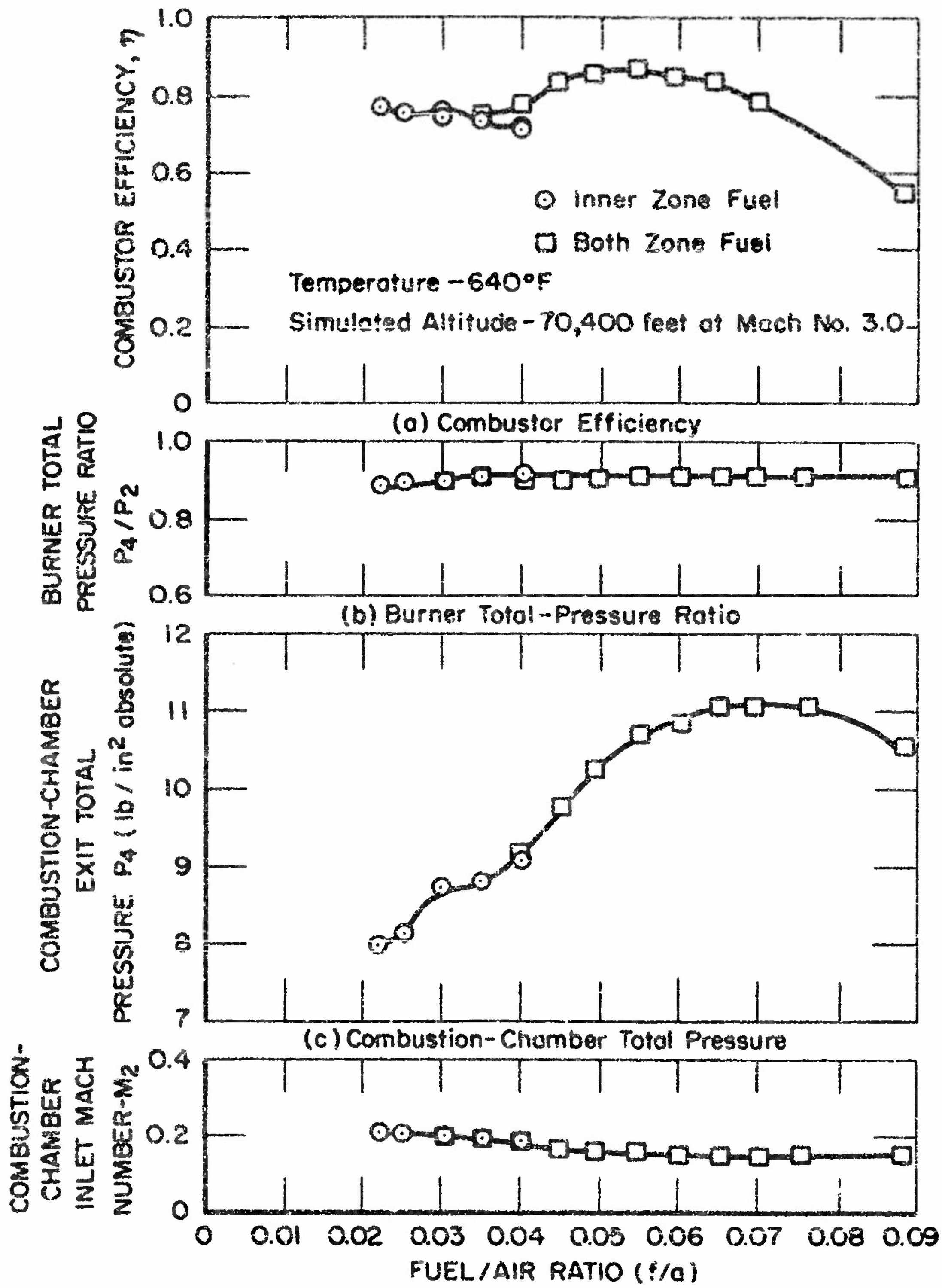


Fig. 10A-7 PERFORMANCE CHARACTERISTICS OF CONFIGURATION 2 (WITH CONTROL SLEEVE) AT A FLIGHT MACH NUMBER OF 3.0

NACA 16-INCH ENGINE (SLOPING-BAFFLE)
Ref. [39], 1953

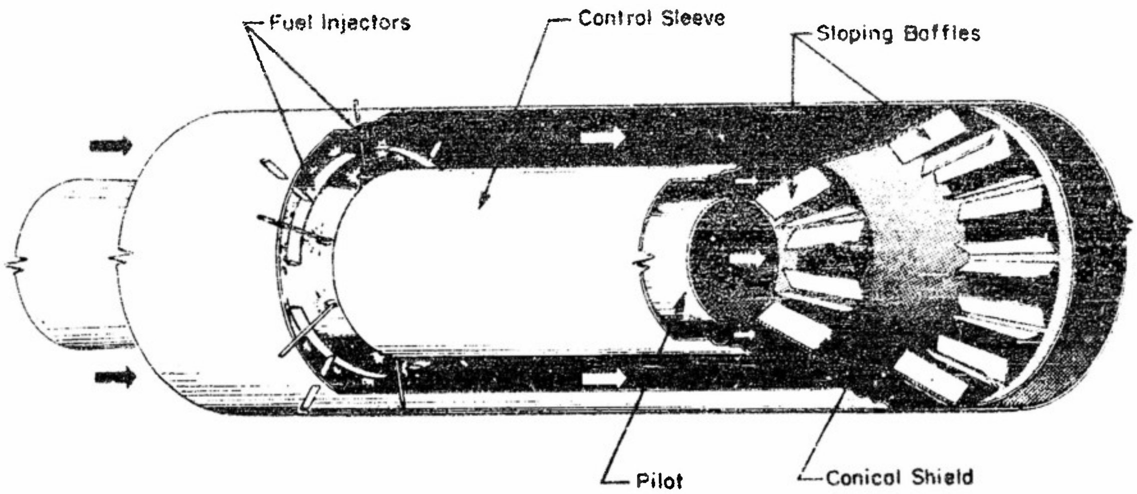


Fig. 10A-8 SLOPING-BAFFLE FLAME-HOLDER CONFIGURATION

I. Expected Missile Performance
No application

II. Type Combustor

A. Pilot - The ramjet is a center-body type with the blunt end of the center body forming the vortex pilot. This pilot consists of a truncated cone, 10.3 inches long, varying in diameter from 7-1/4 inches at the upstream end to six inches at the exit. A single fuel nozzle is used. Air is scopped from the main air supply at two of the three main center body supports and ducted into the pilot through elbows which impart a vortex motion to the air.

B. Spreaders - The sloping-baffle flame holder consists of six U-shaped baffles in the primary zone and twelve baffles in the secondary zone. These are inclined at a 30-degree angle to the combustor axis. The flame-holder open area, projected on a surface parallel to the baffles, is 100 per cent of the combustion-chamber frontal area. The fuel-mixing control sleeve is ten inches in diameter and extends from the fuel injectors

to the flame holder. The sleeve intercepts approximately 20 per cent of the total engine-air mass flow and ducts this air into the primary combustion zone.

III. Ignition

Ground - Electric spark inside pilot

IV. Combustion Chamber

A. Diameter - 16 inches

B. Length - 90 inches (end of pilot to end exhaust nozzle)

C. Inlet Mach Number - 0.14 (approximately)

D. Combustor Drag

E. Exit Nozzle - converging exhaust nozzle

V. Fuel-Injection System

A. Fuel Type - JP-4 is used for pilot and main fuel.

B. Injection System - Fuel is injected through six hollow-cone nozzles rated at 0.5 gallon per minute into the inner-fuel zone and through 16 nozzles into the outer zone. The six nozzles are located in line with the primary-zone baffles. The fuel injectors are located approximately 17 inches upstream of the flame holder.

VI. Engine Performance

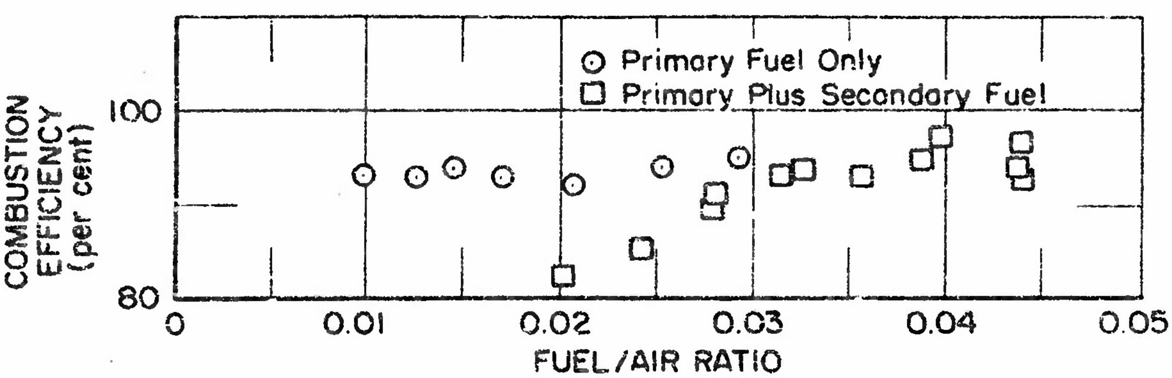


Fig. 10A-9 COMBUSTION PERFORMANCE OF SLOPING-BAFFLE CONFIGURATION

These tests were made using JP-4 fuel, an inlet-air temperature of 600°F, a velocity of 230-260 ft/sec, and a pressure of 31 to 35 inches of mercury absolute.

NACA 16-INCH ENGINE
Ref. [14], 1950

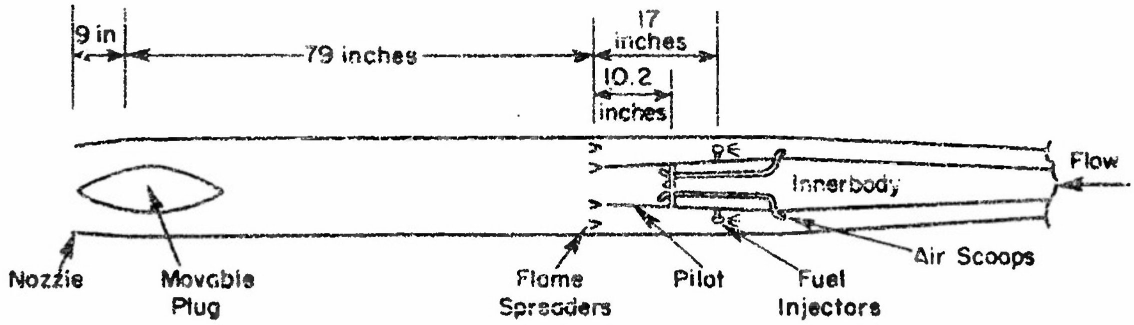


Fig. 10A-10 DIAGRAM OF NACA 16-INCH ENGINE

I. Expected Missile Performance

No application

II. Type Combustor

A. Pilot - The ramjet is a center-body type with the blunt end of the center body forming the vortex point. This pilot consists of a truncated cone, 10.3 inches long, varying in diameter from 7-1/4 inches at the upstream end to six inches at the exit. A single fuel nozzle is used. Air is scooped from the main air supply at two of the three main center-body supports and ducted into the pilot through elbows which impart a vortex motion to the air.

B. Spreaders - The following flame spreaders have been tested:

1. A serrated annular baffle is set at an angle of 35 degrees to the air stream with inner and outer diameters of 9.6 and 14.4 inches. Triangular serrations 2-1/2 inches deep are cut into the outer side. Nine 1-inch sweepback radial gutters connect baffle to pilot. Fifty-five per cent blockage of annular inlet results from this flame holder.

2. Rake-type flame holders with six rake clusters are attached to the pilot by 90-degree radial gutters 2-1/2 inches wide. This gives a blockage of 41 per cent of annular area.
3. The corrugated gutter consists of a series of gutters having a chord of two inches, a spacing of one inch between corrugations, and an angular variation from 35 degrees to 53 degrees included angle. Smaller uncorrugated connecting gutters are welded between the corrugated sections. The flame holder has 53 per cent blockage of the annular inlet.

III. Ignition

Ground - Electric spark inside pilot

IV. Combustion Chamber

A. Diameter - 16 inches
B. Length - 79 inches (approximately)
C. Inlet Mach Number - see performance
D. Combustor Drag - see performance
E. Exit Nozzle - see performance

V. Fuel-Injection System

A. Fuel Type - Various types of main fuel have been tested with propulene oxide used for the pilot.
B. Injection System - Propylene oxide in amounts not exceeding five per cent of the total fuel flow has been burned in the pilot using a single nozzle. The main fuel injector is located 17 inches upstream of the flame holder. Two basic fuel patterns are used. One pattern consists of four arc segments making a manifold to which four commercial spray nozzles are attached, injecting fuel in an upstream direction. The other pattern consists of four arc segments of tubing 1/4-inch in diameter

which has been flattened to reduce the blockage area. Twenty-five orifices 0.028-inch in diameter are drilled in each segment. Every third orifice sprays radially inward. The other orifices are directed upstream.

VI. Engine Performance

TABLE 10A-1

Flame Holder	Fuel Injector	Type Fuel	Fuel-Injection Radius	Nozzle Outlet-Area Ratio	Inlet Static Pressure (lb/in^2)	Inlet Total Temperature (°R)	Smooth-Burning Range F/A	Inlet Velocity (ft/sec)	$\Delta P/q$ at $M_3 = 0.18$	η_c AT F/A - 0.03	F/A - 0.04	F/A - 0.05	F/A - 0.06	F/A - 0.07	F/A - 0.08	F/A - 0.09
Annular	Orifice	Gasoline	6.22	0.739	12.15	540	0.0525 - 0.092	195	2.2				76	69	58	55
		"	"	0.676	"	"	0.042 - 0.079	204-174				92	79	72	62	
		"	"	0.600	"	"	0.038 - 0.079	196-155			73	82	[illegible]	71	62	60
		ANF-32	5.94	0.600	12.4	550	0.575 - 0.008	176-161					67	65	58	50
Rake	Orifice	Gasoline	5.94	0.739	12.5	570	0.0485 - 0.07	206-195	1.4			73	77	68		
		"	"	0.676	"	"	0.046 - 0.0[illegible]	180-179				85	78	70		
		"	"	0.600	"	"	0.0[illegible]7 - 0.074	185-159				73	73	67		
		ANF-32	5.74	0.600	12.75	805	0.05 -> .10	135-119				-	-	58	60	-
Corrigated Gutter	Nozzle	Gasoline	5.32	0.739	11.96	575	0.028 - 0.058	279-205	2.8	48	58	83				
		"	"	0.676	"	"	0.03 - 0.053	247-187		52	56	65				
					Inlet Conditions Are Alongside Pilot (Annulus)											

UNITED AIRCRAFT CORPORATION 14-1/2-INCH ENGINE (MUV-2)

Ref. [22], 1950

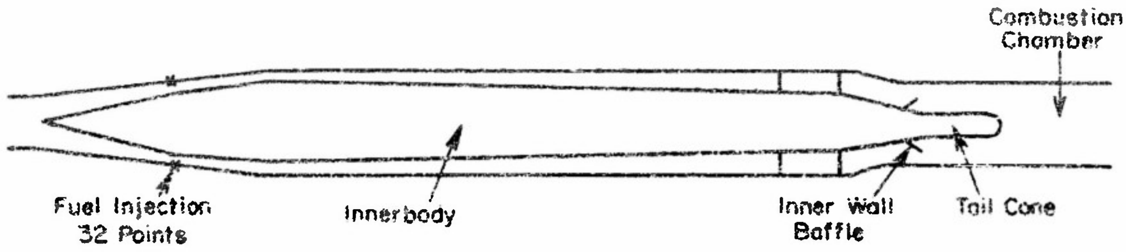


Fig. 10A-11 DIAGRAM OF UNITED AIRCRAFT 14-1/2-INCH ENGINE (MUV-2)

I. Expected Missile Performance

A. Mach Number - 2.0

B. Range - 60 seconds

C. Maximum Altitude - 60,000 to 70,000 feet

D. Launch Mach Number - 2.0

E. Engine Design Air-Fuel Ratio - Air-fuel for maximum thrust

II. Type Combustor

Pilot-Spreader - The spreader-pilot system is an annular baffle mounted on the end of the innerbody wall with an aft conical tail cone section 4.45 inches in diameter. The spreader is two inches high and has a 0.15-inch wall gap. Four oxygen-hydrogen pilots are contained inside the baffle.

III. Ignition

Ground and Flight - Spark ignition at oxygen-hydrogen pilot inlet

IV. Combustion Chamber

A. Diameter - 14-1/2 inches

B. Length - 82 inches from downstream end of baffle

C. Inlet Mach Number - 0.2 at diffuser exit (not full area)

D. Combustor Drag - 0.85 (based on full area)

E. Exit Nozzle - None

V. Fuel-Injection System

A. Fuel Type - Main fuel is 80 octane unleaded gasoline; pilots are fed hydrogen and oxygen.

B. Injection System - The main fuel is injected through 32 atomizing nozzles installed flush with the inner wall 122 inches upstream from the downstream end of the baffle. These atomizers inject the fuel radially into the air stream. Weight ratio of hydrogen and oxygen to the stoichiometric main fuel flow is one part in 15,000.

VI. Engine Performance

TABLE 10A-2

ϕ	Combustion Chamber Inlet (full area)			η_c	S_a	ϕ, Smooth Burning Range	Remarks
Over-all	Pressure (Atmospheres)	Temperature ($^{\circ}$F)	Mach Number				
0.54	2.13	275	0.268	57.4	113	0.55-0.99	Burner unchoked below ϕ = 0.55 and rough above ϕ = 0.99
0.59	2.34	275	0.235	77.0	128		
0.70	2.40	275	0.217	80.0	138		
0.85	2.48	275	0.196	84.1	151		
0.94	2.51	275	0.187	86.7	158		

UNITED AIRCRAFT 4-INCH ENGINE
Ref. [13], 1950

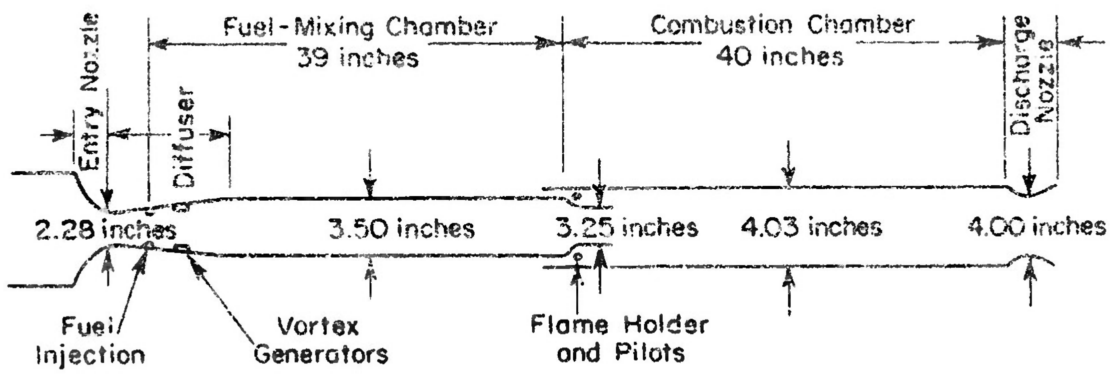


Fig. 10A-12 DIAGRAM OF 14-INCH ENGINE DEVELOPED BY THE UNITED AIRCRAFT CORPORATION

I. Expected Missile Performance

None - Burner is a test stand experimental unit.

II. Type Combustor

A. Pilot-Spreader - The over-all unit consists of a diffuser, a straight section 3.5 inches in diameter, and a combustion chamber four inches in diameter. The flame is held at the inlet of the combustion chamber by a sudden expansion-type side-wall flame holder as shown in Fig. 10A-12. The stream is ignited by six side-wall pilots which inject hydrogen-oxygen flames tangentially into the annular region of the flame holder.

III. Ignition

Ground - Electric spark at hydrogen-oxygen pilots

IV. Combustion Chamber

A. Diameter - 4 inches

B. Length - 40 inches

C. Inlet Mach Number - 0.25 in 3.5-inch-diameter section

D. Combustor Drag - 1.1

E. Nozzle - None

V. Fuel-Injection System

A. Fuel Type - Main fuel is 80 octane unleaded gasoline; small amounts of hydrogen and oxygen are fed to the pilots.

B. Injection System - The fuel is injected radially into the air stream from the diffuser side wall with six pressure-atomizing Hago oil-burner nozzles mounted flush with the outer wall. The injection is 39 inches upstream of the flame holder and operates with pressure drops from 30 to 300 lb/in^2. A set of six vortex generators, consisting of short-span airfoils, project from the diffuser wall 2.2 inches downstream from the fuel injectors. The generators are placed between nozzles and adjacent generators have opposite angles of attack which produce strong counter-rotating vortices.

VI. Engine Performance

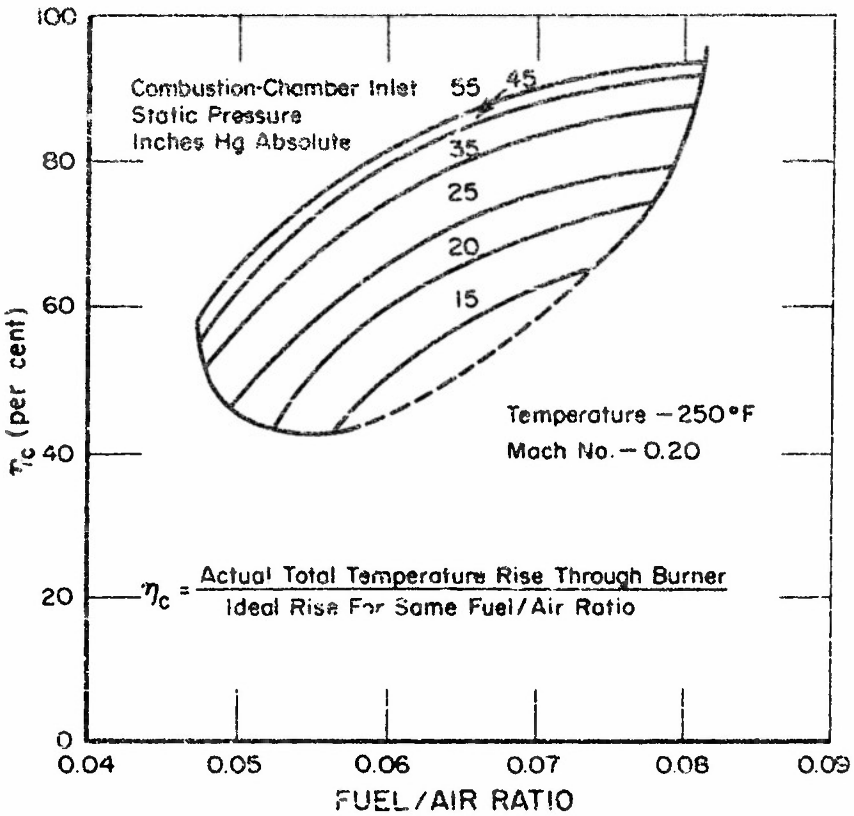


Fig. 10A-13 PERFORMANCE CHARACTERISTICS OF UNITED AIRCRAFT 4-INCH ENGINE

UNITED AIRCRAFT MULTI-UNIT ENGINE

Ref. [33], 1952

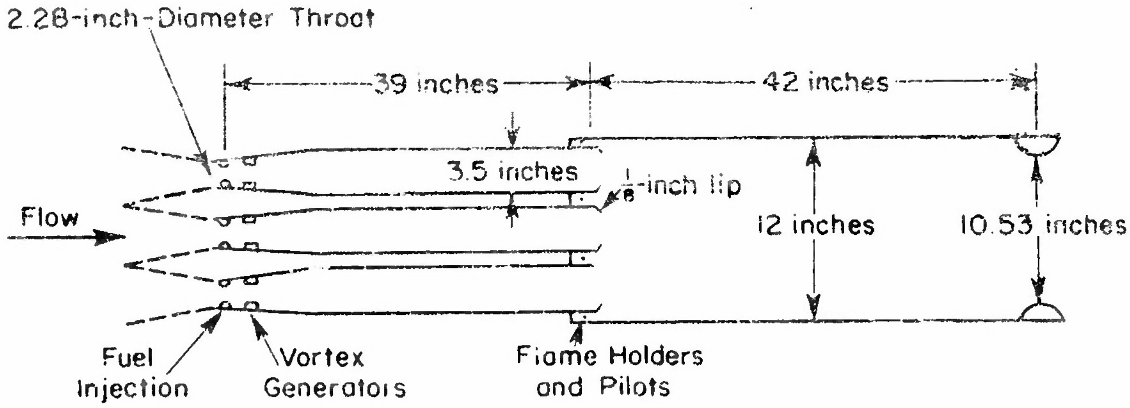


Fig. 10A-14 DIAGRAM OF MULTI-UNIT RAMJET ENGINE DESIGNED BY THE UNITED AIRCRAFT CORPORATION

I. Expected Missile Performance

None - Unit built to demonstrate design principles.

II. Type Combustor

A. Pilot-Spreaders - The engine contains seven separate air passages from the entrance of the supersonic diffuser to the end of the flame holders and a common combustion chamber and exit nozzle (see Fig. 10A-14). Fifteen hydrogen-oxygen pilots were provided in the combustion chamber front bulkhead.

III. Ignition

Ground - Spark ignition at a hydrogen-oxygen pilot

IV. Combustion Chamber

A. Diameter - 12 inches

B. Length - 42 inches

C. Inlet Mach Number - 0.15 (based on 12-inch chamber)

D. Combustor Drag - 1.5

E. Exit Nozzle - 77 per cent

V. Fuel-Injection System

A. Fuel Type - Main fuel is 80 octane unleaded gasoline. Pilots are fed four lb/hr of hydrogen and 16 lb/hr of oxygen.

B. Injection System - The main fuel is injected from six Hago oil-burner nozzles (per unit) mounted flush with the diffuser wall. A set of six air-foil type vortex generators are mounted 2-1/4 inches downstream from the fuel nozzles at an angle of 28 degrees to the air stream alternately right and left.

VI. Engine Performance

See Fig. 10.3-10 (in text).

APL/JHU XPM (6a4) ENGINE

Ref. [6], 1948

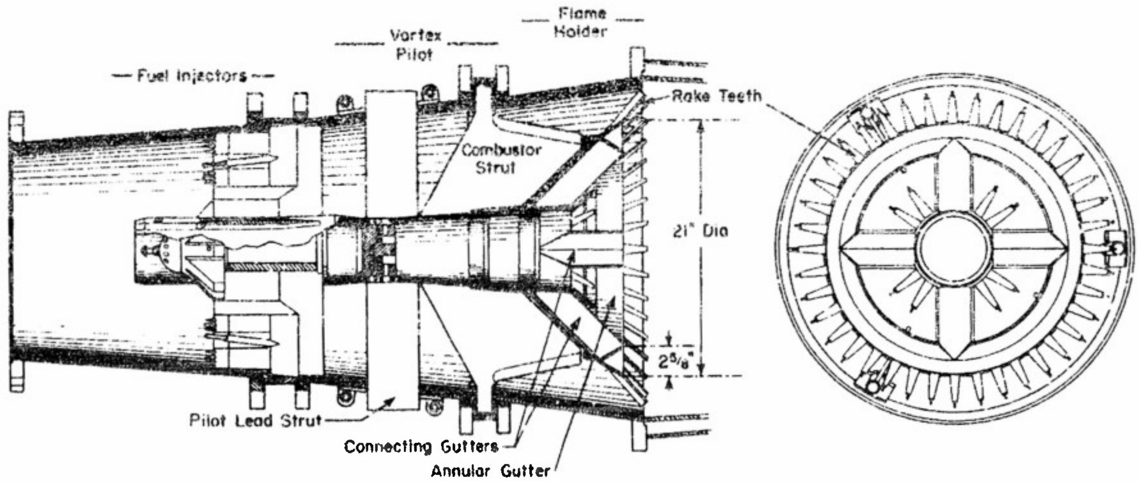


Fig. 10A-15 LABORATORY MODEL OF COMBUSTOR CHOSEN FOR USE IN FIRST RTV-N-6a (XPM)

The flight model was adopted for flare rather than by spark starting.

I. Expected Missile Performance

A. Mach Number - 1.8

B. Range - 40,000 yards

C. Maximum Altitude - 25,000 feet (adequate thrust up to 45,000 feet with diminishing range and efficiency)

D. Launch Mach Number - 1.6

E. Engine Design Air-Fuel Ratio - 18:1

II. Type Combustor

A. Pilot - Central-vortex type, ten inches in diameter at exit

B. Spreaders - Single annular gutter (2-5/8-inch-wide V-gutter) on a 21-inch-diameter circle. Forty rakes with a 3/4-inch base are attached to the outside of the annular gutter. Two 2-3/4-inch radial gutters join together the pilot and annular gutter. The downstream plane of the spreaders is located at the diffuser exit.

III. Ignition

A. Ground - Spark plug inside pilot

B. Flight - Flares

C. General - A 55-per cent blockage starting restrictor is mounted 11 inches downstream from the flame holders.

IV. Combustion Chamber

A. Diameter - 28 inches

B. Length - 63 inches

C. Inlet Mach Number - 0.16 (full area)

D. Combustor Drag

E. Exit Nozzle - Chamber boattails from 28-inch to 24-inch diameter in 72 inches.

V. Fuel-Injection System

A. Fuel Type - The missile carries 350 pounds of JP-1 fuel.

B. Injection System - A Bendix fuel meter is used with an automatic altitude and Mach control with variable-orifice and multi-orifice fuel injection. Fuel is injected approximately 30 inches upstream from spreaders in one stage from 38 contra-stream tubes on which "Tee" spreaders are attached.

VI. Engine Performance

TABLE 10A-3

ϕ Over-all	Combustion Chamber Inlet			η_c	S_a	ϕ, Smooth Burning Range	Remarks
	Pressure (atmospheres)	Temperature (^oF)	Mach Number				
1.01	1.283	350	0.1585	64.4	147	-	
1.00	0.950	350	0.1610	61.2	144	-	
1.02	0.835	350	0.1635	59.8	143	-	
1.01	1.190	212	0.1552	52.4	134	-	
1.01	0.852	210	0.1625	47.5	129	-	
1.02	0.740	213	0.1635	42.1	124	-	
-	-	200	-	-	-	0.65-1.3	35,000 ft, M-2.0
-	-	200	-	-	-	0.72-1.3	38,000 ft, M-2.0
-	-	200	-	-	-	0.90-1.3	43,000 ft, M-2.0

APL/JHU BTV
Ref. [31], 1948

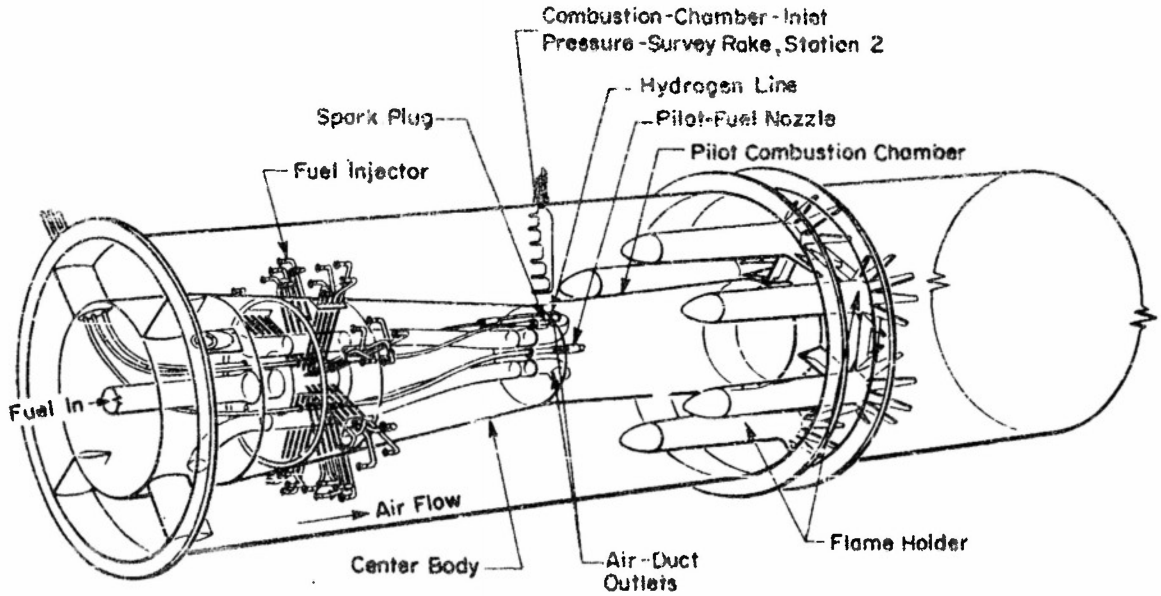


Fig. 10A-16 SCHEMATIC DIAGRAM OF INSTALLATION OF RAKE-TYPE FLAME HOLDER IN BUMBLEBEE 18-INCH RAMJET

I. Expected Missile Performance

A. Mach Number (design) - 2.0

B. Range

C. Maximum Altitude - 45,000 feet (burning altitude)

D. Launch Mach Number - 1.5

E. Engine Design Air-Fuel Ratio - 18:1

II. Type Combustor

A. Pilot - The vortex pilot is attached to the aft end of the innerbody. Air is supplied to the pilot from the diffuser through two air ducts built into the afterbody. Air is discharged into the pilot through two 45-degree-angle nozzles which give the air a swirling motion. The pilot combustion chamber is conical, six inches in diameter upstream and seven inches in diameter downstream. Over-all length is 16 inches.

B. Spreaders - The flame holder consists of six tubes 2-1/2 inches in diameter mounted 60 degrees apart in a ci... 12 inches in diameter. The downstream ends of these tubes are split into eight segments which are flared at a 55-degree angle and the points beveled. The upstream ends are fitted with streamlined noses. The six flared tube rakes are interconnected with gutters and three alternate rakes are connected to the pilot exit with gutters to provide channels in which the flame can travel outward from the pilot to the rakes.

III. Ignition

A. Ground - Electric spark inside pilot, hydrogen is injected to aid ignition

B. Flight - Flares inside cylindrical flame holders

C. Ge eral - Starting restrictors used in flight

IV. Combustion Chamber

A. Diameter - 18 inches

B. Length - 67.5 inches (from end pilot)

C. Inlet Mach Number - 0.2 at $\phi = 1.0$ (measured alongside pilot)

D. Combustor Drag - 1.45

E. Exit Nozzle - None

V. Fuel-Injection System

A. Fuel Type - ANF-32 or 75 per cent ANF-32 and 25 per cent propylene oxide

B. Injection System - About one per cent of the total fuel flow is injected into the pilot through a commercial spray nozzle which operates at approximately its rated delivery of 21.5 gal/hr at a pressure of 100 lb/in^2 absolute. The main fuel-distribution system is located in the rear section of the diffuser center body approximately 35 inches forward of the

downstream end of the flame holder. The fuel flows through 40 tubes radiating out from the innerbody in eight groups of five each. The ends of the tubes are bent forward, giving contra-stream injection. A drop in fuel pressure of from 12 to 20 lb/in^2 is maintained across the system for the range of fuel flows by means of a variable-orifice area plunger valve.

VI. Engine Performance

TABLE 10A-4

ϕ Over-all	Chamber Inlet Along Side Pilot			η_c	S_a	ϕ, Smooth Burning Range	Remarks
	Pressure (atmospheres)	Temperature (^oF)	Mach Number				
-	0.845-0.913	120	0.218-0.180	-	-	0.69-1.06	
-	0.660-0.674	120	0.206-0.195	-	-	0.69-1.06	
-	0.565-0.571	120	0.210-0.195	-	-	0.84-0.99	
-	0.480	120	-	-	-	Limit	
0.792	0.558-0.913	120	-	64	-	-	
0.868	0.558-0.913	120	-	62	-	-	
0.983	0.558-0.913	120	-	59	-	-	
1.100	0.558-0.913	120	-	55	-	-	

APL/JHU COBRA (L4K)

Ref. [21], 1949

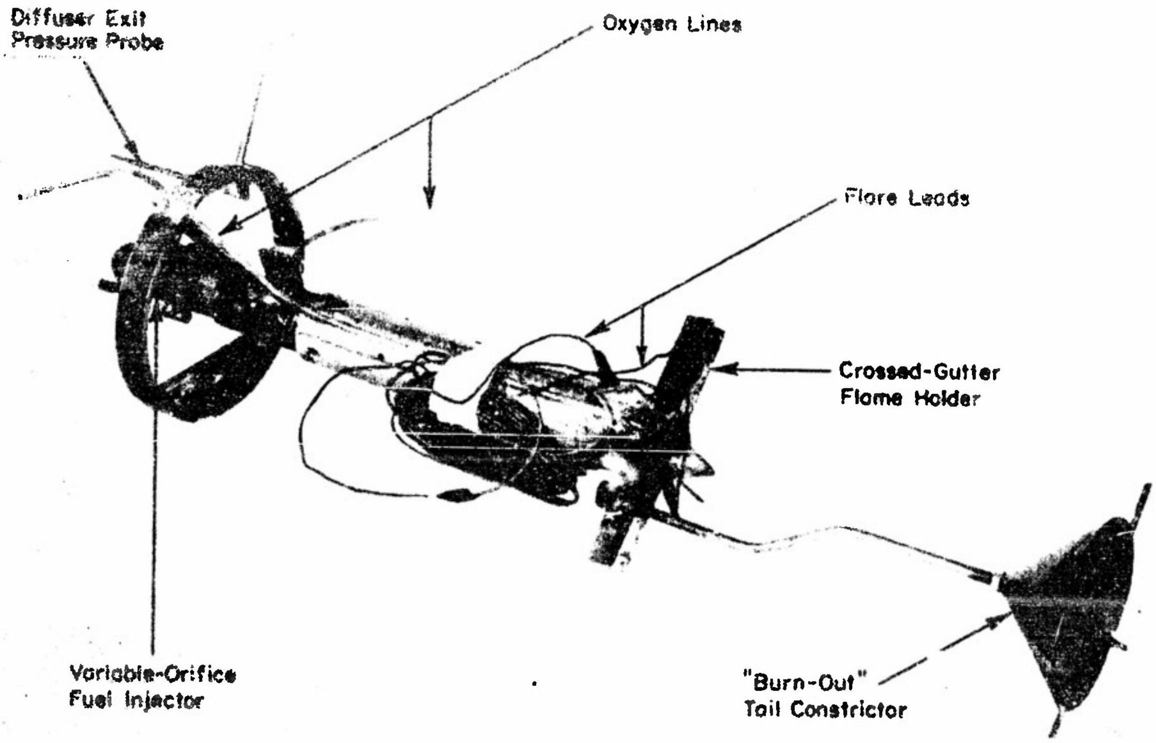


Fig. 10A-17 THE COBRA (L4K) HIGH ALTITUDE FUEL INJECTOR SCHEMATIC

I. Expected Missile Performance

A. Mach Number - 1.3-2.2 (1.6 design)

B. Range - 40,000 yards

C. Maximum Altitude - 60,000 feet (burning altitude)

D. Launch Mach Number - 1.6

E. Engine Design Air-Fuel Ratio

II. Type Combustor

A. Pilot - A central flare holder 1.9 inches in diameter acts as the pilot when small quantities of oxygen are introduced in the zone.

B. Spreaders - A single stage cross gutter, 3/4 inch in width, is attached to the end of the tracer holder.

III. Ignition

A. Ground - Spark plug inside tracer holder

B. Flight - Flare in central holder shown in sketch

C. General - "Burnout" tail constructor as shown in sketch

IV. Combustion Chamber

Same as Cobra (standard)

V. Fuel-Injection System

A. Fuel Type - Propylene oxide is the main fuel; oxygen is fed to the pilot.

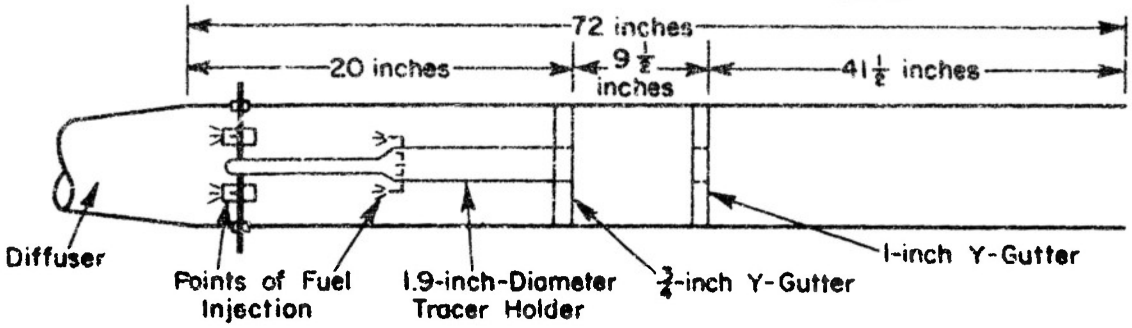
B. Injection System - Oxygen up to 0.0014 lb/sec is injected into the tracer holder. The main fuel is injected at the diffuser exit through contra-stream tubes connected to a variable-orifice fuel injector.

VI. Engine Performance

TABLE 10A-5

ϕ Over-all	Combustion Chamber Inlet			η_c	S_e	ϕ, Smooth Burning Range	Remarks
	Pressure (atmospheres)	Temperature (^oF)	Mach Number				
1.0	3	310	0.23 (approx)	--	169	0.44->1.2	
1.0	2	315	0.23 (approx)	-	165	0.44-1.53	
1.0	2/3	240	0.23 (approx)	80	162	0.7 -1.3	O_2 Pilot
1.0	1/2	205	0.23 (approx)	69	158	0.85-1.43	
1.0	1/3	200	0.23 (approx)	59	150	0.96-1.56	O_2 Pilot

APL/JHU COBRA (STANDARD)
Refs. [7,8], 1947



Note: Upstream Y-Gutters are bisected by Venturi fuel needles.
Downstream Y-Gutter rotated 20 degrees from upstream gutters.

Fig. 10A-18 DIAGRAM OF COBRA (STANDARD) ENGINE DEVELOPED BY THE APPLIED PHYSICS LABORATORY

I. Expected Missile Performance
   A. Mach Number (design) - 1.3-2.2
   B. Range - 40,000 yards
   C. Maximum Altitude - 40,000 feet (burning altitude)
   D. Launch Mach Number - 1.6 at separation
   E. Engine Design Air-Fuel Ratio - 11:1 to 22:1 (metering system range)

II. Type Combustor
   A. Pilot - None
   B. Spreaders - Two-stage Y-gutter (see Fig. 10A-18)

III. Ignition
   A. Ground - Electric spark inside tracer holder
   B. Flight - Flare in central holder shown in sketch

IV. Combustion Chamber
   A. Diameter - 6 inches
   B. Length - 72 inches over-all, 41-1/2 inches from the end of the downstream gutter
   C. Inlet Mach Number - 0.23
   D. Combustor Drag - 2.0
   E. Exit Nozzle - None

V. Fuel-Injection System

A. Fuel Type - 4.3 gallons (missile capacity), JP-1 (75 per cent) plus propylene oxide (25 per cent)

B. Injection System - The fuel system varies somewhat with the purpose of the particular test but, in general, fuel is injected contra-stream from open-type tubes at two stations (see Table 10A-6). The fuel system is under 110 lb/in^2 absolute pressure. The fuel needle pressure drop is compensated by variable-orifice regulator.

VI. Engine Performance

TABLE 10A-6

ϕ Over-all	Combustion Chamber Inlet: Pressure (atmospheres)	Temperature (^{o}F)	Mach Number	η_c	S_a	ϕ, Smooth Burning Range	Remarks
1.0	3	300	0.23 (approx)	73.7	157	0.44-1.14	
1.0	3	550	0.23 (approx)	75.0	159	0.50-1.18	
0.7	3	300	0.23 (approx)	81.0	142	-	
0.7	3	550	0.23 (approx)	79.8	146	-	

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